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FORMATIVE TIME LAGS IN HYDROGEN

being a thesis on

the temporal growth of electrical discharges in
low pressure hydrogen at both low and high overvoltages

by

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SYNOPSIS

Formative time lags (FTL's) have been measured in low pressure hydrogen discharges under both low and high overvoltages.

The low overvoltage experiments were conducted in the range $40 < E/p < 250 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$, and were designed to investigate the relative importance of the secondary processes which could be active in the considered discharges. Results from four experimental tubes are presented, the later tubes having evaporated gold electrodes and a variable inter-electrode distance. The hydrogen was prepared by the electrolysis of barium hydroxide solution, and was purified by passing it through two palladium osmosis tubes in series. Davidson's approximate theory of the temporal growth of discharges was used to analyse the experimental results, and it was found that the cathodic photon process was the predominant secondary process under all the experimental conditions considered, accounting for at least 60% of the secondary action. A preliminary curve of the FTL vs. inter-electrode distance, for constant E/p , pd and overvoltage was obtained for one of the tubes.

The high overvoltage experiments were quite distinct from the lower overvoltage experiments, FTL's being obtained of the order of nano-seconds, about two orders of magnitude lower than in the lower overvoltage experiments. The primary ionization process is sufficient to explain some very short FTL's but some secondary processes have also to be considered to explain others. The high space charges developed in the initial avalanche was seen, in general, to retard the avalanche growth, and to make the value of the primary ionization coefficient

within the gap less certain. Using three experimental tubes having different inter-electrode distances, the effects of varying pressure and inter-electrode distance on the growth of the discharge could be studied at a given E/p ; also, the effect of a change in E/p at constant pressure was studied for the three inter-electrode distances.

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CHAPTER 1
ELECTRICAL BREAKDOWN OF GASES AT LOW
PRESSURES IN UNIFORM FIELDS

1.1 Introduction.

Gases are known to behave as almost perfect electrical insulators, and, under different conditions as almost perfect electrical conductors. The transition between these two states has been, and still is, a fruitful area of investigation. The experimental techniques available, however, in some early investigations are not now considered adequate, and hence some of those early experiments are at present being repeated and extended, in an attempt to obtain a fuller understanding of the physical processes involved in the transition.

In this first chapter, a brief review is given of some of the experiments, conducted at low gas pressures and under static uniform field conditions, which have been performed in this transition region. Particular emphasis is given, where appropriate, to the experimental work in hydrogen, the gas used in the present investigation; and further, attempts are always made to interpret the observed phenomena (such as current growth), in terms of fundamental atomic processes.

1.2 The production of electrical currents between the electrodes of a discharge gap.

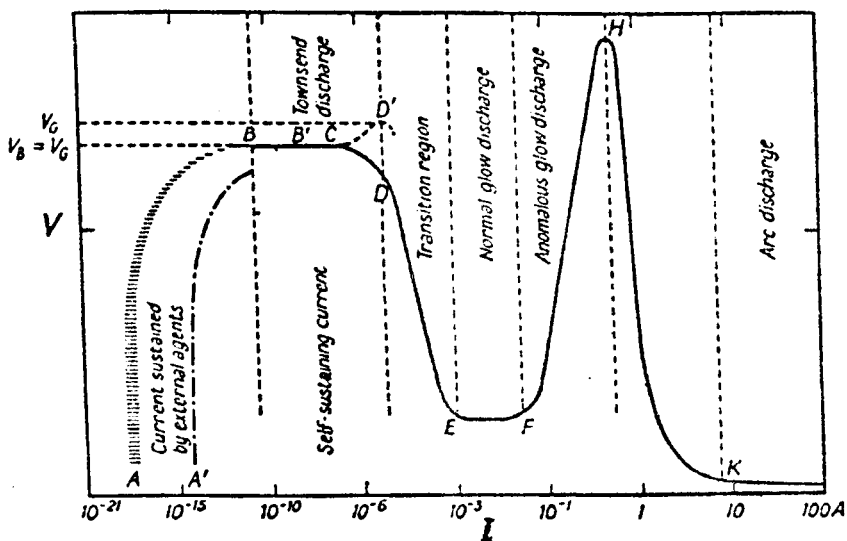
Consider a pair of plane parallel electrodes in a gas, with a potential difference of say 100 V maintained between them. If the cathode is illuminated with ultra-violet light, photo-electrons will be produced which will

be accelerated across the gap towards the anode. On their way to the anode, these electrons will collide with gas molecules which lie along their path; such collisions may be elastic or inelastic.

When an elastic collision takes place with a molecule, that particular molecule does not have its internal structure changed, but it is simply accelerated, while the electron which strikes the molecule loses a small amount of energy (on average an amount $2m/M$, where m is the mass of the electron, M is the mass of the gas molecule, M being much greater than m). It is thus apparent that since the electron loses such a small amount of energy in elastic collisions, it may well be capable of being accelerated until it has quite a substantial amount of energy.

If the electron can acquire sufficient energy, it may well have an inelastic collision with a gas molecule. In such collisions, the electron gives up some of its kinetic energy, which is converted into the potential energy necessary to ionize or excite the gas molecule. Actually the probability that an electron can excite or ionize a gas molecule, varies very much with the energy of the electron, and when the electron energy only equals eV_{ex} , or eV_i (these are the excitation energy and the ionization energy of the considered gas molecule respectively), it can be shown (1) that the probability of excitation or ionization is zero.

Townsend (2) described how these initial photoelectrons, or primary electrons as they are frequently called, are multiplied as they cross the gap. He defined a coefficient, α , the primary ionization coefficient, which is the number of new electrons formed by a single electron moving 1cm in the direction of the applied field.



Schematic characteristic of a gas discharge between flat parallel plates. Scale for the current: logarithmic between 100 and 0.1 amp, still more contracted for lower values of I . — · — · — current with photo-emission from the cathode; · · · · · (CD') positive characteristic of the Townsend discharge; the breakdown potential V_B is lower than the starting potential of the glow discharge V_G ; — (CD) negative characteristic of the Townsend discharge; $V_B = V_G$.

Fig 1

Thus if N_x electrons are considered to be moving in the direction of the field, $N_x \alpha \cdot dx$ electrons will be formed in a distance dx . Integration from $x=0$ (the cathode) to $x=d$ (the anode) yields the expression

$$\frac{N}{N_0} = \frac{I}{I_0} = e^{\alpha d} \quad (\text{for a given } E/p, \text{ see below}) \dots 1$$

where N_0 is the number of electrons in the cloud which leave the cathode, and N is the number at a plane, a distance d from the cathode, while I_0 is the photo-electric current at the cathode, and I is the current at the plane a distance d from the cathode. Equation (1) shows that I is dependent on I_0 ; if I_0 falls to zero, I , too, falls to zero.

Having seen how the initial photo-electrons may be multiplied exponentially as they cross the gap when a comparatively low voltage is applied, it is useful to consider fig 1 showing the current, I , obtained as the gap voltage is further increased. Three major regions of this "discharge spectrum" are apparent; these are the Townsend pre-breakdown region, the glow discharge region and the arc discharge region. The voltage V_3 is called the sparking potential (usually denoted by V_g), which for hydrogen is always somewhat greater than about 300 V, and once it has been reached the gap voltage falls. The current finally attained is limited only by the external circuit and is quite independent of I_0 .

Equation 1 describes the current growth obtained by the action of only the primary ionization process, when the current I is always dependent on I_0 . In order that the current, I , may become self-maintained (as it does once V_g has been reached), it is apparent that some other ionization process must become active which has the effect

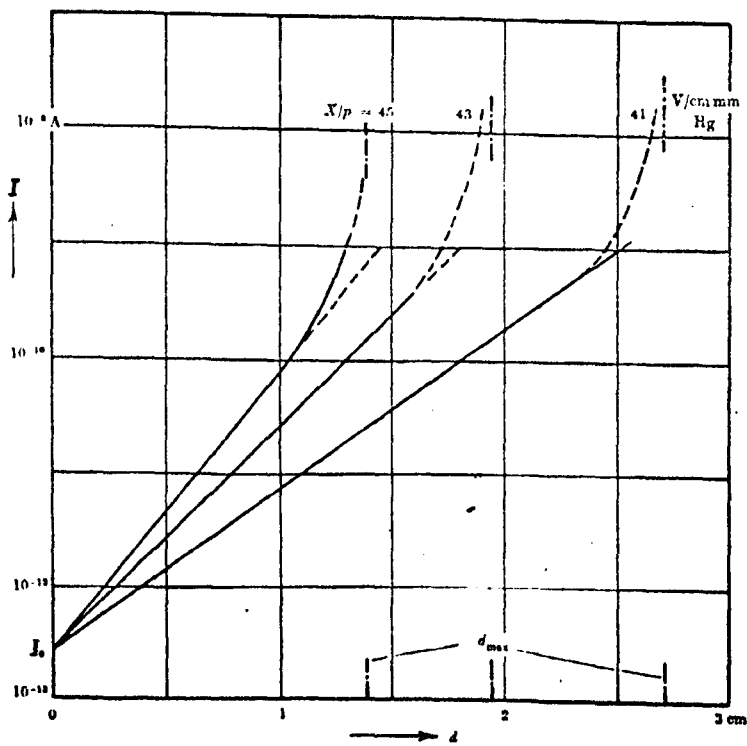


Fig. 49. Multiplication ratio I/I_0 as a function of the electrode separation d for different reduced fields X/p in nitrogen with nickel electrodes ($p = 300$ mm Hg)

Fig 2

of maintaining the number of electrons which pass between the electrodes. i.e. for every electron lost from the discharge another is produced within the gap. There are, in fact, several processes which may act, called collectively "secondary ionization processes".

In order to examine the growth of current across the gap under conditions when both primary and secondary ionization processes may be active, one may investigate the growth of current, I , as the inter-electrode distance, d , is increased, while the electric field, $E = V/d$, is maintained constant. To do this, it is necessary that E may be specified precisely, and this implies that the current density across the gap must not exceed 10^{-8} A.cm⁻² (24). Further, in order that the results of any such investigations may be useful, it is essential that the mean energy of the electrons remains constant, and this may be achieved by ensuring that the ratio electric field to gas pressure ($=E/p$), is maintained a constant. Investigations of this nature have been conducted for a number of years (2,3,4).

Fig 2 shows the shape of typical current growth curves, I being plotted on a logarithm scale against d . The straight part of the curve has been attributed to the primary ionization process described by equation 1, and the upcurving part explained as an increase of ionization due to secondary processes. It has been shown, however, that this convenient explanation is not quite correct (5,6) as secondary processes are active even on the linear part of the curve, the effect of the secondary processes being to increase its slope. Analyses have been developed (5,6), to correct these slopes for secondary effects. When the curve becomes vertical, the current tending to infinity for a finite d ($=d_s$, the sparking distance), the gap

breaks down and the current becomes self maintained.

The equation

$$I = I_0 \frac{e^{\alpha(d-d_0)}}{1 - \left[\frac{w}{\alpha} e^{\alpha(d-d_0)} - 1 \right]} \dots\dots(2)$$

at a given E/p represents the whole curve. w/α is known as the "generalised secondary ionization coefficient" (7), and d_0 is the distance that an electron moves before it acquires the mean energy corresponding to the stated E/p . w/α is defined as being the number of secondary electrons created per ionizing collision in the gap.

It can be seen from fig 2 that different curves are obtained for different values of the parameter E/p , i.e. for different values of the mean energy of the electrons. Townsend first showed that α/p is actually a function of E/p , and by assuming that all electrons, whose energy was greater than the ionization energy of the gas molecule with which the electron collided, did actually ionize that gas molecule, he was able to show that (8)

$$\frac{\alpha}{p} = A \cdot e^{-B \cdot \frac{E}{p}}, \quad (A \text{ and } B \text{ are constants}) \dots(3)$$

Later workers in the field have attempted to refine this equation to make it more generally applicable to gas discharges. Emeléus et al assumed that the electrons followed a Maxwellian distribution and obtained quite good agreement with experimental values for air, hydrogen, oxygen and nitrogen (9); more recently further attempts have been made to derive an even more valid theoretical relationship between α/p and E/p (10).

Having seen that there are two distinct classes of ionization processes which are active in any actual gas discharge, namely the primary process and the

secondary processes, and having examined the role of the primary process, it is now necessary to discuss the secondary ionization processes, i.e. the processes which are necessary for a discharge gap to be able to break down, whenever a sufficiently high voltage is applied across the electrodes.

1.3 Secondary ionization processes.

1.3a Introduction.

There are three agencies which can produce secondary electrons within the gap. These are positive ions, photons, and excited or meta-stable atoms. Each of these agencies could act within the gas itself, or at the cathode, thus resulting in six processes which would be theoretically possible in any actual discharge. In this section these six possible processes are considered, and their relative importance in the type of work discussed in this thesis examined. It is convenient to deal with the gaseous processes and the cathodic processes separately.

1.3b Gaseous processes.

1. Ionization by positive ion collisions with gas atoms and molecules.

This gaseous ionization process was thought to be the very predominant secondary process active whenever a gap breaks down, by Townsend and his school. In 1922, however, Holst and Oosterhuis (11) found for the first time that for any given gas, the sparking potential varied considerably when the cathode surface was changed. This was the first indication that the cathode played any really significant role in determining any discharge parameters, and it was inferred, of course, that w/a was dependent also on the cathode and not wholly on the gas as was once thought.

Following this discovery experiments were conducted to establish whether positive ion collisions with gas atoms and molecules could, in fact produce secondary electrons; and further, the early experiments investigating this process were analysed and soon shown to be unreliable (12). In 1929 the process was shown to be a possible one when Sutton (13) using positive ions of potassium (whose energy was in the range 200eV to 750eV) did, in fact, ionize atoms of neon and argon. Later he was able to extend his studies, and he found that the positive ions of caesium, rubidium, potassium, sodium and lithium (in a similar energy range), could ionize the gas atoms of argon, neon and helium. Later work by Varney (14) has also confirmed that this secondary process is indeed a valid one for some atomic gases, though all the positive ions needed a minimum energy of about 60eV for their effect to be detectable.

Efforts have been made to extend these experiments to the molecular gases. All attempts, however, to produce secondary electrons have always failed with positive ions of energy up to about 400eV, and Loeb states (15) that ionization does not occur "for molecular gases below 500eV of energy per ion". The energy of the positive ions found in low pressure hydrogen discharges can only be a very small fraction of this value, and hence it can be concluded that in hydrogen, under the conditions encountered in the present investigation, ionization of gas molecules by positive ions does not take place in any detectable quantity.

2. Photoionization of gas atoms and molecules.

A photon of frequency ν can ionize a gas atom if $h\nu \sim E_1$, where E_1 is the ionization energy of the atom. Unlike electrons, however, which need energies considerably

greater than the atom's ionization energy to ionize that atom, a photon has its maximum probability of ionization when $h\nu = E_i$. A photon can also ionize an atom if its energy is only a little below E_i (16).

In pure gases, any photons emitted from that gas as a result of a transition from an excited state to the ground state, cannot have enough energy to ionize a similar gas atom, since the ionization energy is obviously greater than any of the possible excitation energies, and thus it can be assumed that in low pressure hydrogen discharges photo-ionization is not a permissible secondary ionization process.

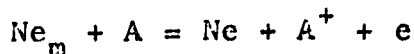
In gas mixtures, however, this process can be of supreme importance. If a photon from gas A, say, had energy $(h\nu)_A$, where $(h\nu)_A$ is greater than $(E_i)_B$, the ionization energy of gas B, then the photon from gas A, can ionize gas B. This process is an essential constituent of the streamer breakdown theory, but as has already been stated it is not possible in pure simple gases.

3. Ionization by excited atoms or metastable atoms colliding with gas atoms and molecules.

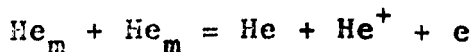
Atoms in the normal excited state have a lifetime of about 10^{-8} sec, and hence it is extremely unlikely that they could produce any significant numbers of secondary electrons by collision with gas atoms, since relatively only very few of them would collide while in the excited state. In some instances, however, secondary electrons have been produced in this way, and perhaps the classic experiments in this field have been carried out by Cario (17), who worked with a mercury, thallium vapour mixture.

These collisions of the second kind (where the potential energy of one atom becomes the energy necessary to ionize another gas atom), though not very common with

normally excited atoms, are quite possible when atoms in the metastable state are considered. Electrons in a metastable^{state} are virtually unable to fall to the ground state in the usual way with the emission of a quantum of radiation, but give up their metastable state energy when they collide with other gas atoms. Because of this, they frequently have lifetimes as long as 10^{-1} sec. The ionization of gas atoms by atoms in this metastable state is very important in some gas mixtures, the process being called the Penning effect (13). An example of this effect is the ionization of argon atoms by metastable neon atoms, i.e.



In pure gases metastables can collide with each other and produce secondary electrons in reactions such as



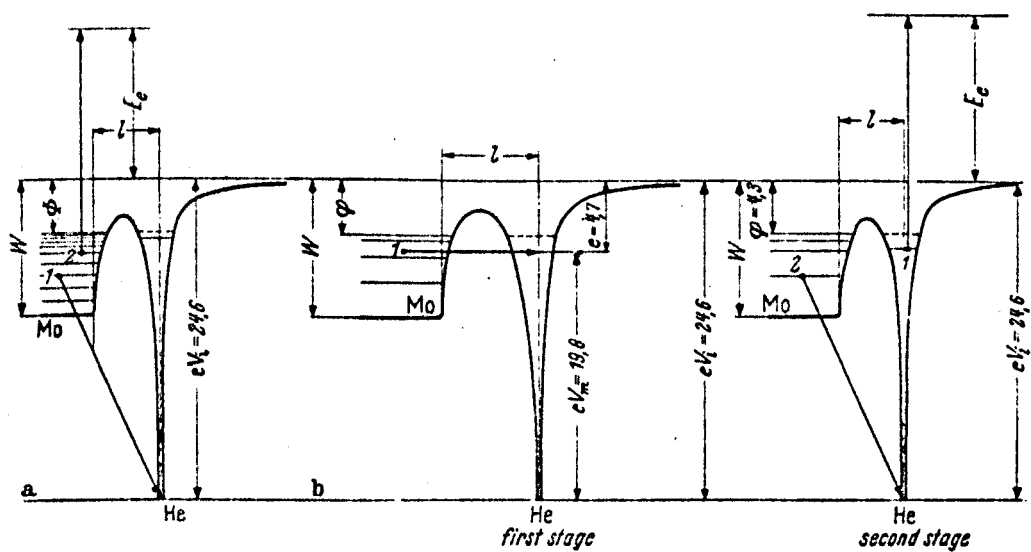
In general this type of reaction is not of any real significance, though it has been detected in the positive column.

Thus in some instances metastables can produce important effects. In pure gases they are generally unimportant, but in gas mixtures they can be very important if the energy of the metastable state is greater than the ionization energy of a different gas atom present in the mixture. Hydrogen of course has no suitable metastable states available, and hence this ionization process is of no relevance to a pure hydrogen discharge.

1.3c Cathodic processes

1. Electron emission by positive ion bombardment of the cathode.

A positive ion moving in an electric field possesses both kinetic energy and potential energy, and hence it is quite conceivable that it can give up either form of this energy on impact with the cathode surface,



Potential energy diagram and electronic transitions for helium ions on molybdenum *a* for direct AUGER neutralisation, *b* for resonance neutralisation followed by AUGER de-excitation.

Fig 3

and so release a secondary electron from that surface.

Consider a positive ion moving in an electric field at thermal velocities. At these low velocities its energy will be predominantly potential energy, and under these conditions there are two possible processes which could result in this energy being given up and an electron being ejected from the cathode. These are:

(i) An Auger transition: This reaction is shown in fig 3 (part "a"). The electric field of the slow moving positive ion distorts the potential barrier at the cathode surface with the result that electrons are able to tunnel through from the upper Fermi level. From the diagram it is clear two electrons are involved at the same time; one goes to the ground state of the positive ion, thus producing a neutral atom, while the other is emitted. The limits of the kinetic energy of the emitted electron are

$$(eV_i - 2\phi) \geq E_e \geq (eV_i - 2W)$$

These equations are satisfied when:

$$eV_i > 2\phi$$

where ϕ is the work function of the cathode surface in eV.

(ii) A two stage interaction: This reaction is also shown in fig 3 (part "b"). The positive ion first captures an electron from the Fermi level of the metal, this captured electron immediately going into an unoccupied level of the same energy in the positive ion, thus producing an excited atom. This newly formed excited atom then reverts to the ground state by ejecting the electron which is in the excited level, but at the same time capturing a second electron from the cathode surface which this time goes straight into the ground state of the atom.

For this process to be possible, it can be shown from energy considerations that

$$eV_{ex} > \phi$$

This two stage reaction is not, however, of any great significance, though it is appreciable in some occasional instances (19), and it can be safely concluded that emission of electrons from cathode surfaces by slow positive ions takes place by predominantly an Auger type transition.

As the energy of the incident positive ions increases, the efficiency of the process increases, thus implying that the kinetic energy of the positive ions is contributing to the secondary emission of electrons. Kapitza (20) has suggested that high energy positive ions when striking the cathode surface might well produce intense local heating of the cathode with the result that there could well be thermionic emission of secondary electrons. Oliphant and Moon (19) obtained some evidence to support this view, when they discovered that the energy distribution of the electrons which were emitted by high energy positive ions from a cathode surface, did in fact have an energy distribution which would have been expected had the emission been thermionic. Little (21), however, states that "it is difficult to conceive that 'temperature' can be assigned to a small volume containing 10 to 20 atoms" and he concludes that "much remains to be done in theory and experiment on this subject".

It is thus apparent that positive ions can be extremely important in producing secondary electrons from the cathode surface. The nature of the mechanism is predominantly due to the potential energy of the positive ions, but since the efficiency of ionization increases

with the ion's kinetic energy, there is some other factor, as yet not fully understood, which is contributing to the production of the secondary electrons. Under the conditions of the work described in this thesis, secondary emission due to positive ions is an extremely important process. It is apparent that the cathode will influence this process, possibly quite considerably, but this will be discussed in section 1.3e.

2. Photoemission from the cathode.

It has been known for a very long time that light incident on some surfaces could release charged particles from that surface(22). More precisely, it is possible for photons to release secondary electrons from a metal surface, if $h\nu$, the energy of the photon is greater than ϕ , the work function of the metal surface. In the work described in this thesis nickel and gold surfaces are used, the work function of these being of the order of 5eV, and thus it is necessary to use photons from the ultra violet part of the electromagnetic spectrum to produce any photo-electrons.

Photons move with virtually an infinite speed (about 10^{10} cm/sec), and hence any secondary electrons emitted by this process, would be expected to appear very soon after the photons are created in the gap. In general this is found to be the case, but if the gas were illuminated with photons whose energy corresponds to one of the excitation states of the gas atoms, the gas atoms will be excited and on decaying to the ground state will emit photons in all directions, which then excite further atoms. This can continue for some little time and is called "resonance fluorescence" (23); the net result is that this process effectively lengthens the time taken for the photons to reach the cathode. This effect can be import-

ant for some gases with metastable states.

Thus photoemission from the cathode surface is an extremely important secondary process, and in fact is the predominant secondary process which is operative under the conditions encountered in the work of this thesis. It should also be noted however, that the cathode surface influences very considerably the efficiency of this secondary process, but this will be considered in section 1.3e.

3. Emission by excited atom or metastable atom bombardment of the cathode:

When the gaseous processes were discussed in section 1.3b it was pointed out that an atom in a normal excited state, would decay to the ground state in a time of the order of 10^{-8} sec, and thus it ^{is} easy to appreciate that no significant number of these normally excited atoms will strike the cathode while in this excited state, and hence no appreciable number of secondary electrons will be produced by them. Atoms in the metastable state, however, have a much longer life-time (of the order of 10^{-1} sec) and hence they will be able to diffuse to the cathode and reach it while still in this excited state. The energy which these excited atoms lose when they decay to their ground state can be used to eject an electron from the cathode. If eV_m (the energy of the metastable state) is considerably greater than ϕ , then the yield from this process can be very considerable.

Thus it can be appreciated that in a gas with suitable metastable states, this secondary process can be extremely important. Results quoted by Little (21) indicate that this process can actually be the most efficient of all the secondary processes, except possibly for high energy ions. In mercury vapour and gases such as helium and neon, where suitable metastable states exist

this process is very important. In hydrogen, however, which has no metastable states, the emission of electrons from the cathode by excited atoms can be entirely neglected.

1.3d Summary of the ionization processes active within a gap in a low pressure hydrogen discharge: It can be seen from section 1.3b that there are no secondary ionization processes which can be active in the gas in these discharges. This implies that the only gas ionization process which will be active in such discharges will be the primary ionization process (known as the α process). This then indicates that the hydrogen discharge will not become "self maintained" by gas processes alone, and thus the actual "break down" of the gap will be dependent on the cathode, which suggests that very great care must be taken in order to specify precisely its surface nature.

The importance of the cathodic secondary processes is now clear. In the discharges considered later in this thesis, there are two possible secondary processes which could be operative. These are the positive ion and the photoemission processes. Coefficients are used to describe all the possible processes, but only the coefficients describing these two processes will be described here. γ , the symbol used for the positive ion process, is defined as being the number of electrons liberated from the cathode per single ionizing collision in the gas. Thus γ is only dependent on the cathode surface, and is seen to be independent of the actual current which flows between the electrodes. The coefficient δ/α is used to characterise the photoemission from the cathode, and is defined as being the number of photo-electrons emitted from the cathode per ionizing collision in the gas. w/α ,

the generalised secondary ionization coefficient which can be written as the linear sum of the coefficients used to characterize the 3 possible processes (24), can in this case be written as the sum of just two terms, namely

$$\frac{w}{\alpha} = \gamma + \frac{\delta}{\alpha}$$

1.3e Influence of the cathode on the secondary ionization processes:

The earlier discussion has revealed just how important the cathode surface is in low pressure hydrogen discharges. It must be remembered, however, that its importance was not realised by Townsend when he first tried to establish the basic physics of gaseous electronics. It is easy to appreciate how he failed to detect the cathode's significant role when it is realised just how primitive were the vacuum techniques of those early days. It was not possible to evacuate the experimental tubes to any lower pressures than what is today regarded as "backing pressure". This implies that it was quite impossible to obtain really clean surfaces, there being a tarnish layer over the most carefully prepared surface! These tarnish layers resulted in basically similar surfaces being used in these early experiments, the contaminants on the cathode effectively obscuring the differing underlying base metals.

Once the cathode's role was discovered work was undertaken to determine just how important is the cleanliness of its surface, some parameter being measured as the cathode is subjected to varying treatment. Parameters which have been used are the minimum sparking potential (V_g) and the cathode's work function, ϕ .

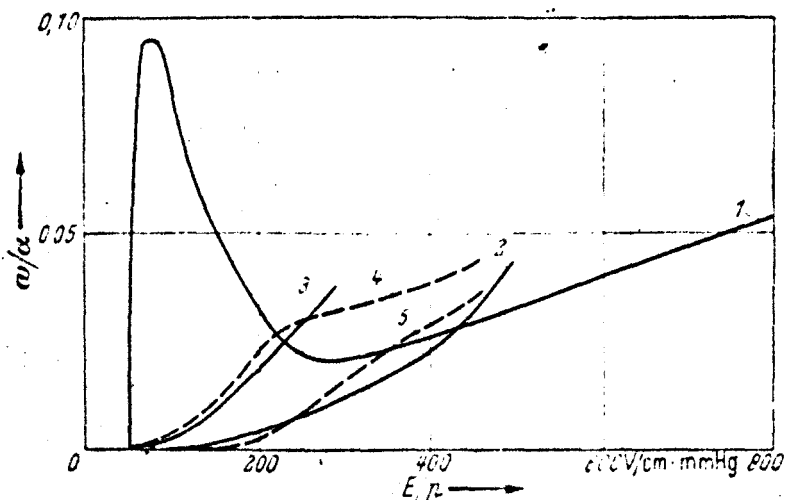
Llewellyn Jones and Davies (25) followed changes in the minimum sparking potential as a function of time as the cathode was first being cleaned and later, as an alien metal was being sputtered on to it. Their work showed that prolonged heating at 400 °C was not very effective in removing the last traces of tarnish layers, but they found that prolonged bombardment of the cathode with hydrogen positive ions did produce a very clean surface.

This work and later work in this laboratory has shown that it is of the utmost importance to specify the cathode surface very precisely, and to use a reproducible surface. For this investigation ultra-high vacuum techniques have been used, and the conducting layer on the cathode has been an evaporated layer of gold, the gold having earlier been very carefully heated in a current of hydrogen. This will be discussed more fully later.

1.3f Distinguishing the secondary processes in low pressure hydrogen discharges:

There are two distinct types of discharges which have to be considered in this section. These are the "steady state discharge," i.e. the discharge which takes place when the potential difference across the discharge gap is less than the sparking potential, and the non-steady state discharge which takes place once the potential across the gap exceeds V_g . It is possible, at least in hydrogen discharges, to obtain an estimate of the relative importance of each of the two possible secondary processes, in both types of discharge. These discharges will now be examined separately.

In the steady state discharge it is possible to estimate the relative importance of the δ/α and the γ processes by a study of the w/α versus $\frac{E}{p}$ curves.



Secondary coefficients ω/α in diatomic gases. Curve 1. N_2 with Pt cathode [BOWLS: Phys. Rev. 53, 297 (1938)]. Curve 2. H_2 with Ag cathode after 30 min. bombardment with H_2^+ ions [LLEWELLYN JONES and DAVIES: Proc. Phys. Soc. Lond. B 64, 519 (1951)]. Curve 3. H_2 with Cu cathode possibly covered by a thin tarnish film [LLEWELLYN JONES: Phil. Mag. 28, 192 (1939)]. Curve 4. H_2 with Cu cathode after 48 hours degassing. Curve 5. H_2 with Cu cathode after 116 hours degassing (LLEWELLYN JONES and DAVIES: loc. cit.).

Fig 4

In section 1.3c it was seen that the γ effect was predominantly dependent on the positive ions' potential energy, the kinetic energy of the ion only playing a secondary role. The potential energy of a positive ion is independent of $\frac{E}{p}$, and thus it can be seen that the γ process will be essentially constant as $\frac{E}{p}$ changes, there being only a very small increase in γ as $\frac{E}{p}$ increases. The δ/α process, however, behaves quite differently. The number of photons emitted with a particular energy will depend on the number of excitations to the level corresponding to that energy. If N_x electrons are considered to be drifting across the gap under the action of the electric field, the number of excitations to a particular level in a lamina of width dx , will be proportional to a term of the form $N_x \alpha' dx$. In this lamina there will be $N_x \alpha dx$ ionizing collisions in the gas, and hence the number of photons falling on the cathode per ionizing collision will be proportional to a term of the form α'/α . Thus the value of the coefficient δ/α will be dependent on this ratio α'/α . This ratio will increase as $\frac{E}{p}$ decreases, since its magnitude will be dependent on the mean energy of the electrons. Thus it is found that as $\frac{E}{p}$ decreases, the value of δ/α increases.

Fig. 4 shows some w/α versus $\frac{E}{p}$ curves. As w/α increases slowly as $\frac{E}{p}$ increases, this increase is interpreted as an increase in the magnitude of γ , the positive ion process. Where, however, w/α increases rapidly as $\frac{E}{p}$ decreases, this is interpreted to imply that the δ/α process is increasing in magnitude. In this way it is possible to obtain at least some estimate of the relative importance of the two possible secondary processes.

Consider now the non-steady state type of discharge. The time which is taken for the discharge to build up to a value which can produce breakdown will be very dependent on the particular secondary process which is active. The time of flight of the photons can be regarded as being negligible, and hence the speed of the δ/α process will be dependent on the drift velocity of the electrons w_- , which on drifting across the gap excite the molecules in the gap. The speed with which the γ process operates will be dependent on the drift velocity of the positive ions w_+ , as they drift towards the cathode. Now w_+ is about 100 times slower than w_- , and hence secondary electrons will be created by the δ/α process very much more quickly than by the γ process. This implies then that measurement of some time dependent factor in the discharge might very possibly be able to give some indication as to the relative importance of the two possible processes, if the experimental results can be reliably analysed. The time dependent phenomena which are usually measured are the growth of the discharge current and the time which is taken for the potential across the discharge gap to collapse. These results should, of course, give the same result when the results are correctly analysed, because the time taken for this voltage to collapse is calculated by estimating the time taken for the current to rise to a value which is sufficient to produce the observed voltage collapse. Thus essentially these apparently different determinations are measuring the same thing in different ways, but it can be seen that the measurement of one of these quantities might very well give some information as to the relative importance of the two cathodic processes in the non-steady discharge.

In the work which is described later in this thesis, the time taken for the gap voltage to collapse when the gap was slightly overvolted (less than 3 per cent above the sparking potential), has been measured in order to obtain some estimate of the relative importance of the two possible secondary processes. Further, the growth of the discharge current has been measured when the gap was overvolted to such a degree that space charge effects became very important. These investigations are reported fully in chapters 5 and 6.

1.4 Paschen's law.

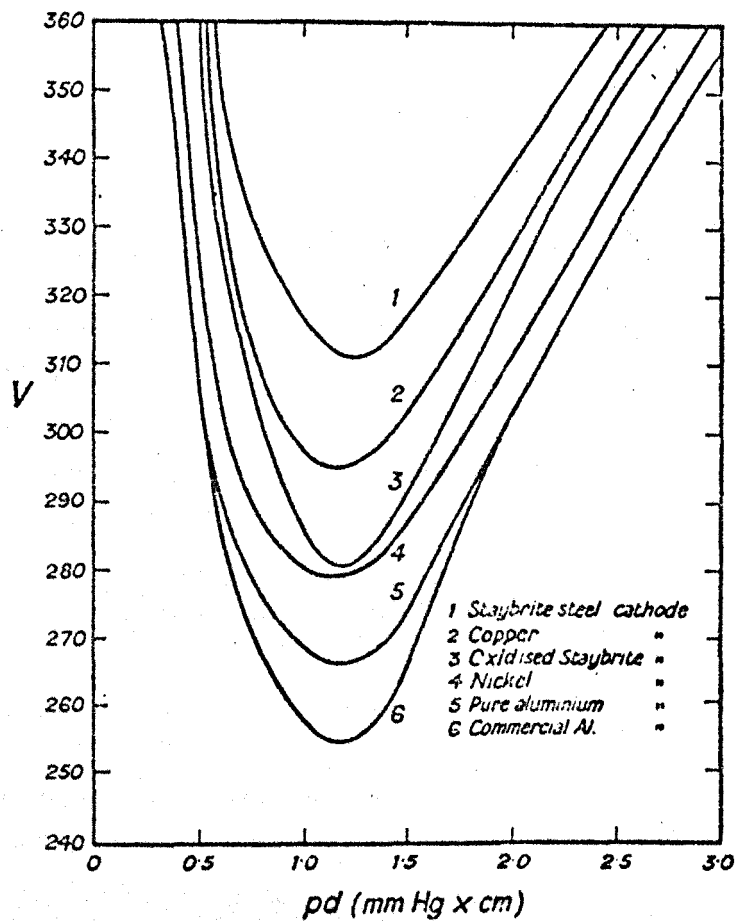
In section 1.2 the pre-breakdown current growth curves were considered, and it was seen that the complete curve could be expressed by the single equation:

$$I = \frac{I_0 e^{\alpha(d-d_0)}}{1 - \frac{w}{\alpha} [e^{\alpha(d-d_0)} - 1]}$$

The gap is said to break down and the current become self maintained when, for a given potential difference, the current I remains finite as I_0 tends to zero. The behaviour of the right hand side of the above equation, when the numerator tends to zero, can only produce an finite current, I , if the denominator, too, tends to zero. i.e. the gap will break down when:

$$1 - \frac{w}{\alpha} [e^{\alpha(d-d_0)} - 1] \text{ tends to zero.}$$

The potential difference at which the gap breaks down has already been called the sparking potential, V_s , and is now seen to be that potential



Breakdown voltage curves in hydrogen
for different cathode materials.

Fig 5

difference, which, independent of the initial current, can just maintain a small current.

Paschen's law states that V_g is a function of the product of the pressure, p , and the sparking distance, d_g , only.

$$\text{i.e. } V_g = f(p.d_g)$$

This was first stated as an empirically established fact (26,27), but it can in fact be derived by analytically treating Townsend's breakdown criteria(24).

The general shape of a V_g vs. $p.d_g$ curve, i.e. a Paschen curve, can be established by considering the primary ionization process which must be active in the gap at breakdown. As the gas pressure is lowered, the collision frequency with the gas molecules decreases, and hence in order that ionization of the gas molecules takes place in the necessary quantities to produce breakdown, it becomes necessary to increase the ionization probability. This is achieved by increasing the field as the pressure is lowered. As the pressure is raised, however, a point is reached where the collision frequency increases to such an extent that the only way for the electrons to acquire sufficient energy to ionize the gas molecules in sufficient quantities, is for the field to be increased again. This then implies that the V_g vs. $p.d_g$ curves will be expected to show a minimum. Typical curves are shown in fig 5.

There have been quite a number of reported divergencies from Paschen's law. In this laboratory, such effects have been observed in both hydrogen and mercury (28), and have been attributed to an effect caused by a change in the geometry of the gap, i.e. in the ratio electrode diameter, D , to the inter-electrode distance, d . As d/D gets smaller, the number of photons which are lost

from the discharge gap is reduced, this implying that the coefficient δ/α is increased in magnitude for a given potential; hence it is to be expected that at a given p.d, the gap may well breakdown at lower potentials as d is reduced. This indicates that care must always be taken to specify the electrode geometry of the experimental tube, whenever quoting results.

In the work that is described later in this thesis, the time taken for the discharge to become self-maintained when a voltage V , greater than V_s , is applied to an illuminated gap, is measured as a function of the percentage overvoltage ($=100(V-V_s)/V_s$). When V_s is measured in hydrogen, by determining the minimum voltage which will produce a self-maintained current, both the δ/α and γ processes may be active. For breakdown times greater than d/w_+ , the positive ion crossing time, it is apparent that both secondary ionization processes may be active, but when breakdown times of the order of d/w_- , the electron transit time, are being measured, it is apparent that the γ process cannot be active and hence any reference to V_s as determined by the method mentioned above has no real meaning. With these very short breakdown times it is thus impossible to determine a true value for V_s (i.e. the value V_s would take if the only permissible secondary process were photon action at the cathode), and hence the results are presented in a different manner. This is discussed further in section 2.4.

1.5 Formative time lags and statistical time lags.

In section 1.2 it was seen that the application of a voltage greater than V_s across a discharge gap causes the gap to break down, the discharge current becoming self-maintained and being limited only by the external circuit.

This breakdown does not, however, take place instantaneously. It is of course first necessary to have a charged particle within the gap before any current can flow between the electrodes. The frequency of the appearance of charged particles between the electrodes will vary as the background radiation varies, and hence the time taken between the application of a potential greater than V_g , and the appearance of the initiatory charged particle between the electrodes, will vary statistically and is called the statistical time lag (STL). Further, breakdown does not occur at the moment the initiatory electron appears within the gap, a finite time elapses before the current builds up to the point where it becomes self-maintained, i.e. until the voltage across the gap collapses. This second time lag is called the formative time lag (FTL).

Thus it can be seen that the time taken for the gap to break down when a sufficiently high voltage is applied is made up of two quite distinct parts, namely the STL and the FTL. In any experimental investigation, only the total time lag may be measured and hence in order to measure either one of its components the other must be reduced to zero. The investigation in this thesis is concerned with FTL's and hence the STL has to be reduced virtually to zero. The means by which this may be achieved has already been mentioned, namely the continuous irradiation of the cathode with a U.V. lamp of an intensity sufficient to produce a new photo-electron at the cathode at, say, every 10^{-7} sec when FTL's of the order of 10^{-6} sec are measured, and at every 10^{-10} sec when FTL's of the order of 10^{-9} sec are measured.

In section 1.3f it was shown that the FTL varies as the relative importance of the δ/α and the γ processes

varies. More precisely, it is apparent that V_s is determined by the values of w/α and ad , but the time taken for the gap to break down once V_s has been reached is determined by the ratio $\frac{\delta}{\alpha} / \frac{w}{\alpha} = \frac{\delta}{w}$. As the ratio approaches unity the FTL is expected to decrease. Further, as the potential applied to the gap increases above V_s , the values of α and w/α are enhanced and thus the FTL is again decreased. Many workers have been engaged in measuring FTL's at low overvoltages (up to 2% above V_s), the results obtained being plotted in the form shown in fig 8. For these experiments it is assumed that at such low overvoltages, the value of E/p for a complete curve is essentially constant, and further, the value of w/α is actually taken to be constant over this small E/p range. The decrease in FTL as the overvoltage is increased is thus attributed wholly to the increase of α . The shape and position of these curves is very dependent on the ratio δ/w , and by comparing the experimental results with curves obtained using a mathematical analysis some estimate of the value of δ/w may be obtained.

It is also apparent from fig 8 that as E/p increases, the displacement of these curves from the origin also increases. This is attributed to a reduction in the ratio $\frac{\delta}{\alpha} / \frac{w}{\alpha} = \frac{\delta}{w}$, and hence an increase in $\gamma / \frac{w}{\alpha}$, as E/p increases. As the slower positive ion process increases in importance, the FTL's are increased.

Thus at low percentage overvoltages it can be seen that the breakdown process can be regarded as being a result of Townsend's primary and secondary ionization processes. The current is imagined as increasing under conditions where there are no space charges (due to

positive ions). Many workers have maintained that at low percentage overvoltages this is so, and mathematical theories have been developed(see section 2.6) where such space charge effects are completely neglected. Other workers, however, have maintained that the development of space charge fields within a discharge gap influences overwhelmingly the temporal growth of the discharge particularly at high percentage overvoltages. In such very fast breakdowns it is apparent that space charges do develop which modify the breakdown growth rate, but the modification produced can be such as either to increase the growth or to decrease the growth. The shape of the α/p vs. E/p curve gives an indication as to how space charge effects will alter the FTL. In hydrogen at low E/p , while α/p increases faster than linearly with E/p , the space charge shortens the FTL while at higher E/p 's the FTL is increased. The whole problem is very complex, however, and will be dealt with more fully in chapter 6 when the experiments conducted in this investigation under conditions where space charges are very important are discussed.

Thus it can be seen that the FTL's which are measured at low percentage overvoltages may be interpreted in terms of the basic Townsend processes, while at higher percentage overvoltages, such a growth process is modified very markedly by the development of positive ion space charge fields.

1.6 Conclusion.

In this chapter an outline has been given of the basic physics of gaseous electronics in uniform fields at low pressures. The experimental work which is discussed in this thesis consists of a study of FTL's at both high

and low percentage overvoltages, and the principal contributions to such a study, from both experimental and theoretical viewpoints are briefly discussed in the next chapter.

CHAPTER II

REVIEW OF PREVIOUS WORK

2.1 Introduction

The temporal growth of electrical discharges in gases has been investigated for many years. Some investigators measured the time taken for the gap voltage to collapse, while others measured directly the actual growth of current between the electrodes. Experiments have been conducted over a large range of E/p , and under conditions of both high and low percentage overvoltages. In this second chapter a brief review is given of perhaps the most significant work in this very broad field. The early work is briefly discussed, as a matter of historical interest, though some of the experimental techniques used then are of no real relevance to the experiments carried out in this investigation; and since it was fairly generally thought that these results indicated that the Townsend theory of breakdown was sometimes inadequate, the experiments conducted to investigate the postulated transition point between the different breakdown mechanisms are also discussed. Some recent growth of current measurements are considered as these are important forerunners of some work conducted in this laboratory, and this investigation on the growth of current under high overvoltage conditions. Finally, some quite recent breakdown measurements under low overvoltage conditions are discussed in more detail, since they too have direct relevance to the bulk of the earlier work described later in this thesis.

2.2 Early practical investigations.

In order to measure FTL's (i.e. the time taken for a gap to break down once the necessary voltage has been applied across the electrodes, between which is an adequate supply of electrons), it is necessary to be able to observe some phenomenon which can be taken, quite unambiguously, to imply that the gap has indeed broken down. Workers have varied very markedly in that choice. Rogowski (28) in 1928, working at high overvoltages with a centimetre spark gap, measured FTL's as short as 10^{-3} sec, by using an oscilloscope to measure the time taken for the gap voltage to collapse. Such short times then seemed to imply that the Townsend breakdown model of primary and secondary ionization processes was not valid under Rogowski's experimental conditions, but this will be considered more fully in section 2.3. The following year Tank and Graf (29) extended the investigation to lower pressures and again were able to obtain reproducible breakdown times.

In the early 1930's, Dunnington, Lawrence and White (30) in America started some interesting FTL measurements in air at pressures ranging from 200 mm Hg to atmospheric pressure. Unlike the German workers who took the collapse of gap voltage as indicating breakdown, they took the appearance of a spark as signifying that the gap had broken down. They positioned a Kerr cell, which was placed between crossed Nicols, in the path of the light from their spark. Some of this light travelled along another path and was reflected by a mirror into the Kerr cell. The shutter on the cell was opened and closed by a pulse travelling along a delay line, and by carefully tilting the mirror it was possible to obtain two images of the spark channel side by side after a very

small time interval . They were able, in fact, to measure breakdown times as short as 10^{-8} to 10^{-9} sec. Their work is interesting in that they used an optical effect to measure such small times, but too much significance cannot be put on their results as it is possible that they were not measuring the actual FTL, but merely part of it.

White improved the techniques of the initial investigation and extended the study to other gases, including N_2 , O_2 , CO_2 and He at atmospheric pressure. Further, he investigated how the photo-electric current, I_0 , influenced the FTL, discovering that with very high I_0 's, V_g could be reduced by as much as 10 per cent. White, however, used the light from a second spark gap to produce his I_0 , which, of necessity, had a finite rise time which tended to introduce errors.

Wilson (31) further improved White's techniques, by ensuring that there was always a supply of photo-electrons available between the electrodes, by constantly irradiating the cathode. His U.V. source, however, was not really adequate and thus his results showed some statistical fluctuations. Wilson, incidentally, applied a static backing potential of $0.99 V_g$, and then he suddenly overvolted the gap by switching in a desired potential in series with the backing potential.

These early results at quite high percentage over-voltages (usually up to 90 per cent), when plotted in the form FTL versus percentage overvoltage produced the now familiar curve which tends asymptotically to each axis. Their FTL's were in the range 10^{-6} sec down to a little less than 10^{-8} sec, and although these results contained quite considerable errors which were acknowledged by the

experimenters themselves, their results are extremely interesting in that they show some of the ingenious ways that the absence of modern day electronic equipment was compensated for in the early temporal growth studies.

The following year, Newman (32) used an entirely different experimental method to measure these short times. He had a series of electronic voltmeters along an electrical transmission line which were able to determine the voltages of an incoming surge wave at precise time intervals in relation to another timing wave. His work enabled him to declare that: "it appears that the time lag of breakdown is a rather definite...function of the overvoltage...".

Thus it can be seen that before the war years the general variation of the FTL with percentage overvoltage had been established, at least for the very small FTL's at high overvoltages. All the experiments, however, had serious unsatisfactory features, producing very high experimental errors. Fletcher, in 1947 (33) using transmission lines to produce his voltage pulses was able to measure nano-second FTL's to a much higher accuracy. His apparatus is very interesting in that his experimental gap was carefully positioned within a co-axial cable, care being taken to avoid any sharp discontinuities which might have produced undesired reflections, and by discharging his pulse-forming coaxial cables, he was able to produce pulses as long as 100 nsec having an amplitude as high as 120 kV. Fletcher developed a mathematical theory based on the streamer mechanism with which he was able to calculate FTL's which were in very good agreement with his experimental values. Fletcher's techniques have been adopted by later workers and have also been used in this laboratory in experiments which will be described in

section 2.4.

Having seen that these very short time lags had been obtained by several workers over some twenty years, it became necessary to attempt to establish positively the nature of the breakdown process active under these high overvoltage conditions. In the next section the experiments which were conducted by Fisher and his associates to determine the point where the Townsend breakdown model ceases to be adequate are described, and it is shown that in fact no such point is found.

2.3. The apparent failure of the Townsend breakdown model and the attempts to find the point where this process ceases to be applicable in actual discharges.

In the last section, several experiments have been discussed in which very short FTL's were measured in a variety of ways. These very short times were about one hundred times shorter than the positive ion transit time, thus suggesting that the positive ions could play but a negligible role in the breakdown mechanism. The photo-electric process was at first not considered and hence it was thought that the breakdown was being achieved without the action of any secondary processes at the considered high values of the product p.d. There were, in fact, other indications that at high p.d the breakdown did not follow the familiar Townsend model. The pre-breakdown current versus gap distance curves consisted only of a linear part, no upcurving being observed similar to that found at low p.d when the secondary processes became appreciable. Further, the nature of the spark channel itself at high p.d suggested that the breakdown mechanism was different from that at low p.d where the spark channel was very much more diffuse. Finally, as mentioned in section 1.3b, the cathode was

never observed to play any significant role in the breakdown mechanism. Thus it can be seen that there was, in fact, quite a number of indications that the Townsend breakdown model was quite inadequate to account for the experimental data at these high p.d values.

Alternative theories were proposed by Raether (34) and by Loeb and Meek (35), known as the "Canal Theory" and the "Streamer Theory" respectively, in order to account for the experimental results found at p.d values greater than about 150 cm. mm Hg. Raether suggested that most of the FTL consisted of the time that an electron took to build up to the magnitude where its space charge field was comparable with the applied field. He then postulated that secondary avalanches, initiated in front of, and behind the head of the initial avalanche by photon absorption, build up more rapidly in the enhanced field caused by the space charge. Thus two "streamers" of ionization were developed which appeared to move one towards the anode, and the other towards the cathode at very much higher velocities than the velocity of the initial avalanche. This then implies that the whole spark channel would be established very soon after the space-charge field of the original avalanche becomes of the order of the applied field. Raether was able to express these ideas in a mathematical form that explained the general shape of the FTL versus percentage overvoltage curve, and further, he predicted the correct order of magnitude.

The Canal and Streamer theories were introduced, as has been shown, in an attempt to derive a model which would be in accordance with the experimental results found at high p.d. It was fairly generally thought, in the early 1940's that there had to be two types of

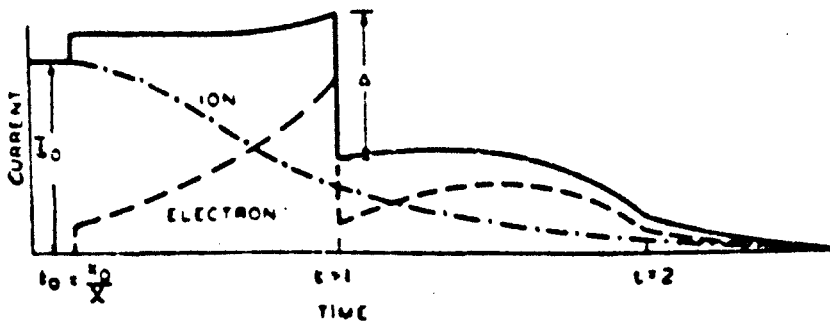
theory to account for the breakdown characteristics at high and low p.d, and it was thought that the transition point was somewhere between a p.d of 200 (34) and 1,000 cm. mm Hg (35). Fisher and his school initiated an investigation in 1946 (36) which attempted to find this transition point.

Fisher developed very stable power supplies which enabled him to take measurements of FTL's at percentage overvoltages as small as 0.015 per cent. His cathode was continuously illuminated by U.V. light and he measured his FTL's, as is now quite usual, with an oscilloscope. His original work in air (37) was later extended to N_2 and Ar (38, 39), but he was unable in all cases to find the postulated transition point. At low overvoltages, however, he found FTL's which were unexpectedly long, 100 μ sec at 0.02 percentage overvoltage, while at 2.5 percentage overvoltage this had been reduced to about 0.1 μ sec. Fisher maintained that these long time lags were the result of two processes acting together, these being firstly a suitable secondary mechanism to maintain and perhaps increase the pre-spark current, and secondly space charge distortion due to the large number of positive ions within the gap. Further, Fisher presented a linear plot of FTL's against gap distance for a given percentage overvoltage. These results were obtained for pressures between 200 mm Hg and atmospheric pressure, but it is not actually stated whether these determinations were made at a constant E/p .

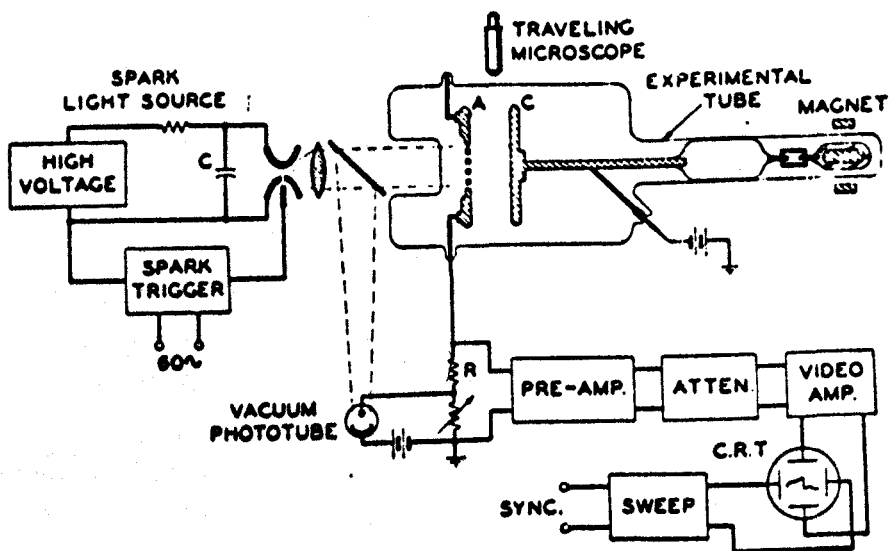
Thus it can be seen that the experiments which were initiated solely to detect this postulated transition point failed completely to do so, and it was not long before the whole streamer type breakdown process was being vigorously attacked. Workers at Swansea, under

Llewellyn Jones pointed out that the Townsend breakdown mechanism had been rejected principally because it was thought that that model could not produce breakdown times as small as those observed, and that this was generally believed even though at that time the mathematical treatment of the temporal growth of discharge currents on the Townsend model had not been adequately developed. Since then mathematical theories based on the Townsend mechanism have been refined and it has been shown that breakdown times of the order of micro-seconds may very well be observed at only 1 per cent overvoltage. These theories are developed more fully in section 2.6. Further, experiments were conducted (40) to investigate the linear pre-breakdown relationship with the gap distance at high p.d and they were able in fact to show that these plots did indeed become curved at high enough values of d. The narrower spark channel at high p.d is really only to be expected when it is realised that the higher pressure will tend to reduce the lateral diffusion of the charges.

Thus it can be seen that the basic objections to the Townsend model have, in fact, been removed. It is apparent, however, that the basic Townsend model is not adequate to describe breakdown under all conditions. The basic mechanism is sometimes modified by severe space charge distortion of the applied field, such as is found when highly overvolted gaps are discharged. Avalanches that have a "streamer appearance" have actually been photographed, and it is indeed foolish to pretend that they do not exist, but at the same time the existence of a streamer may be regarded as a "modified Townsend breakdown" as opposed to an entirely different breakdown mechanism. Having thus established that the early FTL



b. Typical Oscillogram



a. Hornbeck's Apparatus

Fig 6

measurements do not imply a complete rejection of Townsend's breakdown model, some current growth measurements will be discussed in the next section which were initiated in an attempt to determine the secondary ionization processes that were active in some electrical discharges in various gases.

2.4. Some growth of current measurements.

Hornbeck in 1951, initiated some growth of current measurements (41) which were designed to enable him to get some estimate of the relative importance of the possible secondary ionization processes, and further, he was able to obtain values for positive ion drift velocities (w_+) in N_2^{Ne} , O_2^A and SO_2^{Ne} , at a range of E/p up to about $2,000 \text{ v}(\text{cm.mm Hg})^{-1}$, and at very low E/p (less than $4 \text{ v}(\text{cm.mm Hg})^{-1}$), the electron drift velocity (w_-).

His experimental technique was to apply a voltage across his experimental gap which was a little lower than V_s . He then released a burst of U.V. light onto the cathode (lasting only 10^{-7} sec) and then observed the resulting currents which passed between the electrodes, on an oscilloscope. A block diagram of his apparatus is shown in fig 6 together with a sketch of the type of oscillogram which was obtained. It might be useful to consider briefly how such a trace is obtained. The photoelectric current produced by the 10^{-7} sec pulse of U.V. light flows to the anode at time $t = 0$, and since it would be so large compared with the following currents it is not shown on fig 6. These initial electrons on passing across the gap, ionize a number of gas molecules, the nearest positive ions being formed at a plane a distance x from the cathode. The exponential distribution of positive ions then drift towards the cathode at their characteristic drift velocity, w_+ , and after a time x/w_+ ,

the first ones reach the cathode, and there commence releasing secondary electrons. This is shown clearly on fig 6, in that the current remains constant for a time x/w_+ (while the exponential distribution of positive ions drift towards the cathode), and at the moment the positive ions reach the cathode, the contribution of the positive ions to the current is reduced and the contribution of the secondary electrons starts to increase. After a time $t = 1$ which corresponds to the time taken for a positive ion to drift across the whole gap, the last of the positive ions which were initially created reaches the cathode and thus there is a sudden drop in the number of secondary electrons produced by the positive ions striking the cathode, and hence there is a sudden drop in the electron contribution to the total current as shown in fig 6. The secondary electrons on drifting across the gap produce further positive ions which on striking the cathode produce further secondary electrons. The contributions of these charged particles to the current flow is shown on the diagram as being the current flowing after a time $t = 1$. The total current falls to zero a little later, because the total potential across the gap was less than V_g , and hence the secondary processes cannot produce electrons in sufficient quantities to produce a self-maintained current.

Thus it can be seen that by careful examination of his oscillograms, Hornbeck was able to obtain some very useful values for w_+ (and at low E/p for w_-). He obtained mathematical expressions which together with his experimental data enabled him to calculate the relative contributions of the possible secondary mechanisms, obtaining a value of about 50 per cent for the ion contribution under his experimental conditions.

In 1954 Varney (42) obtained some further current growth measurements. His mathematical expressions were more rigorous than Hornbeck's, and his experimental techniques more refined, but since the general approach is so similar to Hornbeck's it is not really useful to discuss Varney's experiments in any detail.

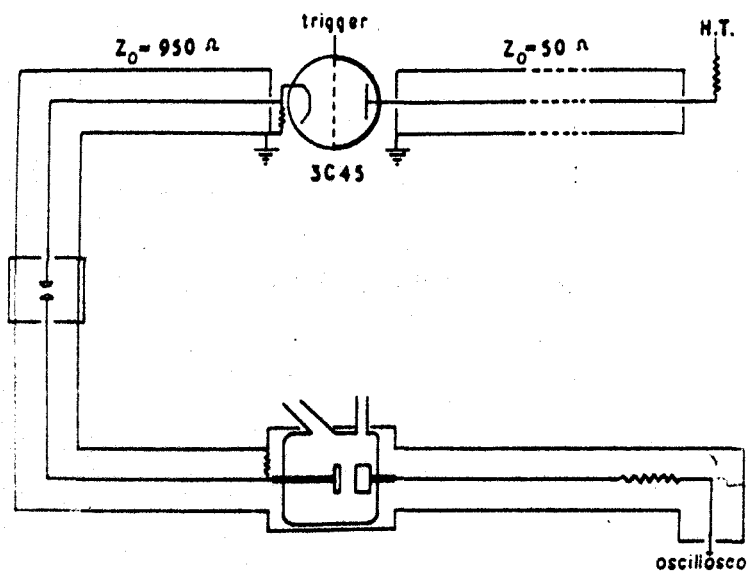
Also in 1954 Bandel (43) observed the growth of current actually as his experimental gap was breaking down, i.e. during the actual FTL. His experimental results and the subsequent mathematical analysis enabled him to claim that the almost exponential increase in current in the middle of the time lag was due to secondary mechanisms, and that the final upcurving which produced breakdown was due to space charge distortion of the electric field.

Having briefly considered the contribution which some Americans made in the 1950's to the study of the actual growth of current in the electrical discharges, it is important to be aware of Raether's German group's contribution over the last few years. Raether, of course, was responsible for the Canal Theory of the temporal growth of electrical discharges, and hence his group have been particularly interested in the growth of discharges under conditions where the development of the discharge followed a streamer-like model, i.e. they have been particularly interested in the growth characteristics of the discharge under conditions where high space charge fields are developed.

Measurements of the current growth in H_2 under potentials about equal to V_g have been made by Kluckow(44), in an experiment which was similar in principle to Hornbeck's. There were, however, significant differences

in the experimental conditions in that Kluckow was interested in a very low E/p at higher pressures where all detectable secondary action was due to the δ/α process, unlike Hornbeck, where the δ/α contribution to w/α was negligible. Kluckow was able to show just how important a role was played by space charge distortion of the applied field, in that he was able to cause his gap to break down when $\frac{w}{\alpha} \cdot (e^{\alpha d} - 1) < 1$, and at times less than d/w_+ , by substantially increasing the number of his initiating charged particles which were positioned between his electrodes. In this work, the oscillograms obtained showed some small oscillations at their very beginning. Schlumbohm (45) has studied these in very much more detail, and by a careful analysis has managed to obtain some values for w_- which fit in well with other w_- determinations.

For completeness, Raether's experiments (46) using photo-multipliers must be mentioned. In chapter 1 it was pointed out that on Townsend's breakdown theory, a discharge current may become self-maintained when $\frac{w}{\alpha} \cdot (e^{\alpha d} - 1) = 1$. Raether wished to investigate the growth of a single avalanche between his electrodes; in order to do this, it is essential that the initial electron is multiplied in the single avalanche by a factor of 10^6 i.e. it is required that $e^{\alpha d}$ is approximately 10^3 . If this is to be allowed, then w/α must be about 10^{-6} which is about three orders of magnitude less than found in hydrogen. Because $w/\alpha = 10^{-3}$ in hydrogen, this implies that in order to study the growth of a single avalanche in hydrogen, a potential very much greater than V_s must be applied across the experimental gap and consequently the displacement current would be very much higher than the current of the actual avalanche. Raether realised



Dawson's Apparatus

Fig 7

the difficulty in making electrical measurements on this single avalanche, and instead "observed" the avalanche by the light which is given off by the excited atoms and molecules as they return to the ground state. This technique is extremely valuable and analysis of the experimental results enabled values for w_- to be obtained for an E/p of up to $150 \text{ v}(\text{cm.mm Hg})^{-1}$.

Having briefly considered some of the techniques used in the study of the growth of current at potentials both greater than and less than V_g , it will be convenient to close this section by considering some work very recently undertaken by Dawson (47) in this laboratory. He used co-axial cables to produce his voltage pulses and set out to study FTL's which were of the order of the electron transit time, d/w_- , in hydrogen. His apparatus is shown in fig 7. He used a commercial cable of characteristic impedance 950 ohm to create his pulses, and by the use of a secondary spark gap to sharpen his pulse was able to obtain a reasonably square pulse of up to 200 nsec, which could be discharged across his experimental gap by triggering a hydrogen thyatron in the circuit, with a small commercial pulse generator. Dawson's experimental tube was mounted along the axis of the inner conductor of his co-axial cables in a similar way to that used by Fletcher, and it was found that on discharging the cables across the experimental gap, the displacement current as the capacitance of the gap was charged, was quite sufficient to trigger the Tektronix 519 oscilloscope. The ensuing current flow was then displayed on the oscilloscope. Dawson defined his FTL as being the time between pulse application and the first observable current rise. Because of his high characteristic impedance cable (950 ohm), this first observable current was smaller than

10^{-2} A, this comparing very favourably with about 20A which had to flow in Fletcher's 50 ohm cables before he could detect a current flow.

With FTL's in the nano-second range, it is apparent that the positive ion secondary process can but have a negligible effect on w/α , and hence the only possible secondary process contributing to breakdown can be the photon, δ/α , process. Further, the quite common way of plotting results, i.e. FTL vs. percentage overvoltage, does not have a great deal of meaning since V_g , determined by a static measurement as being the lowest voltage to maintain a current between the electrodes even when I_0 is reduced to zero, is the sparking potential of the gap when both the γ and the δ/α processes can contribute to w/α . Then, to calculate percentage overvoltage for conditions when the γ process cannot be active, implies really that the calculated percentage overvoltage will be greater than the "real" value which cannot be determined. Dawson adopted the procedure of taking a series of FTL measurements at a given pressure and plotting them in the form FTL vs. E/p for that pressure.

Dawson was, of course, particularly interested in measuring breakdown times which corresponded to the time which a single electron took in crossing the gap, and assuming that the breakdown was by a single avalanche he calculated a value for the electron drift velocity, w_+ , from the equation

$$I = \frac{qw_+}{d} e^{aw_+t}$$

where q is the electronic charge, and then plotted these apparent drift velocities against E/p , again for varying pressures. Thus when FTL's were obtained which were quite long he would obtain very low values of w_+ and

similarly for very short FTL's he would obtain very high values of w_- . From a study of these curves Dawson concluded that all his results had been markedly affected by space charges, and further he obtained very different results at different E/p 's. At low E/p , where he calculated that the gas multiplication should have been quite sufficient to produce breakdown in the time which an electron takes to drift across the gap, he found FTL's were often 2 or 3 times this time, presumably resulting from a decrease in w_- due to space charge effects. As E/p increased he found the current increased at a faster rate than that predicted by the earlier equation, and at higher E/p still, he measured FTL's which were very much shorter than expected. These very short FTL's being much smaller than the electron crossing time, while the multiplication of a single avalanche was thought to be only 10^3 or 10^4 as compared with the 10^8 which was required to produce breakdown as seen on the oscilloscope. Some further aspects of his experiments will be discussed in chapter 6, when some results taken in the course of this investigation will be presented.

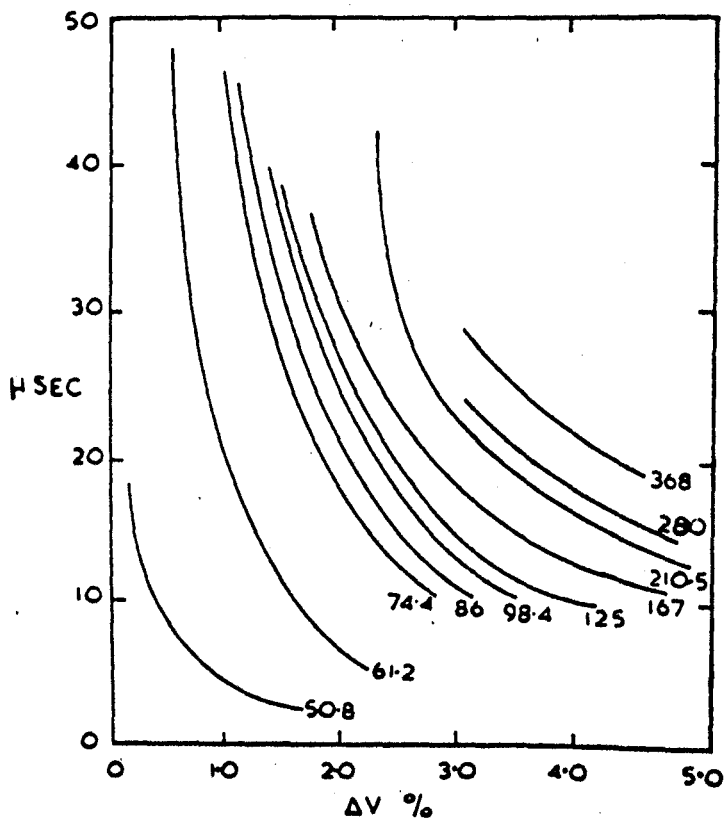
Having briefly reviewed some of the more important contributions to the current growth field, which have been conducted over the last 15 years under quite different experimental conditions, it will be helpful to discuss some recent FTL measurements which have been made under low overvoltage (less than 2 per cent overvoltage) conditions at Swansea and in this laboratory.

2.5. Recent FTL measurements at low overvoltages.

Workers at Swansea, under Llewellyn Jones, have been engaged on a study of the temporal growth of discharges under low percentage overvoltages for a number of years. They usually had large (5cm diameter) bulk metal

electrodes which were previously polished and washed very carefully in an attempt to get clean electrode surfaces. Particular care was taken to ensure that their voltage impulse had the necessary short rise time, by reducing all inductance paths to a minimum, and by making the capacitor through which the impulse voltage was applied an integral part of the discharge tube envelope. The glass wall of the envelope was the dielectric between two silver plates; this arrangement created a capacitor with a very high leakage resistance and also allowed the lead from the impulse generator to the anode to be kept very short. They applied a static backing potential (less than V_g) across the electrodes, which had been electronically stabilized to better than 0.1 per cent, and they then suddenly overvolted the gap by applying a potential impulse which had a rise time of $2 \cdot 10^{-8}$ sec, and which had an error in the potential of less than 1 per cent. All statistical variations were eliminated by irradiating the cathode with soft X-rays.

Their experiments have emphasised just how important it is to have thoroughly clean electrode surfaces. Their preliminary results (48) were obtained with electrodes which had received a single cleaning treatment, and were still covered with a tarnish layer which resulted in an appreciable scatter (a standard deviation of between 10 and 40 per cent), in the measured FTL's, and also caused some difficulty in measuring V_g . Later they ran a glow discharge between the electrodes for some hours, and then baked the system at 350°C while pumping, again for several hours. This treatment resulted in the electrodes being thoroughly cleaned of all tarnish layers and at overvoltages less than 0.5 per cent, their standard deviation was less than 5 per cent, and this was reduced to less than 3 per cent at overvoltages greater than 2 per



Formative time lags in hydrogen. Dependence of growth time upon overvoltage for copper electrodes after 36 hours treatment.

Fig 8

cent.

Their results were presented by drawing curves of FTL's vs. percentage overvoltage for different values of E/p . As E/p was increased, the displacement of their curves from the origin increased, this effect having already been mentioned in section 1.6. It should be pointed out, however, that E/p ($= \frac{V_g}{pd}$) was changed by altering p , while d remained constant throughout.

These experimental curves were then compared with theoretical curves which were obtained by solving some equations produced by Davidson's analysis of the temporal growth of the current, and which will be discussed more fully in the next section. Such a comparison of theoretical and experimental curves may be used to obtain an indication as to the relative importance of the γ and the δ/α processes. Dutton et al (49) compared such a set of theoretical curves with the published results of Fisher and Bederson (37), and though admitting that it was not possible to obtain an exact fit they claimed that "it is possible to obtain fair agreement between the theoretical analysis and the experimental results...". Such an analysis revealed that the dominant secondary process under their experimental conditions was the δ/α process, but there was also some detectable action from the γ process. In the same paper, Dutton et al claimed that it was possible to conclude that the same primary and secondary ionization processes, which produce the observed growth of the pre-breakdown currents, also produce in the non-steady state a rapid decrease of the FTL with increasing overvoltage. They further concluded that the actual FTL is dependent on the ratio δ/w ($= \frac{\delta/\alpha}{w/\alpha}$), and FTL's of the order of 10^{-6} sec were obtained by using Davidson's analysis at overvoltages of only 1 or 2 per cent when the δ/α process is the dominant

VARIATION OF THE FORMATIVE TIME LAG
WITH REPETITION PERIOD

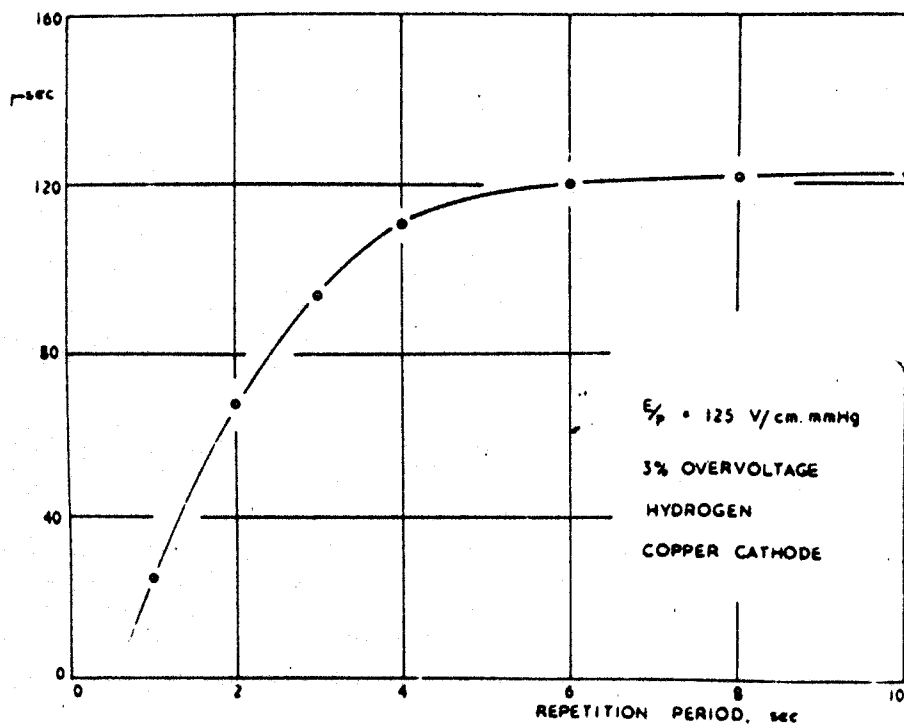


Fig 9

secondary process.

In a later, more complete investigation (50) in hydrogen, Morgan found the relative importance of the γ and δ/α processes as E/p changed. He found that the γ process increased in importance as E/p increased, but that even at low E/p , the positive ion action was still appreciable. His FTL vs. percentage overvoltage curves are shown in fig 8.

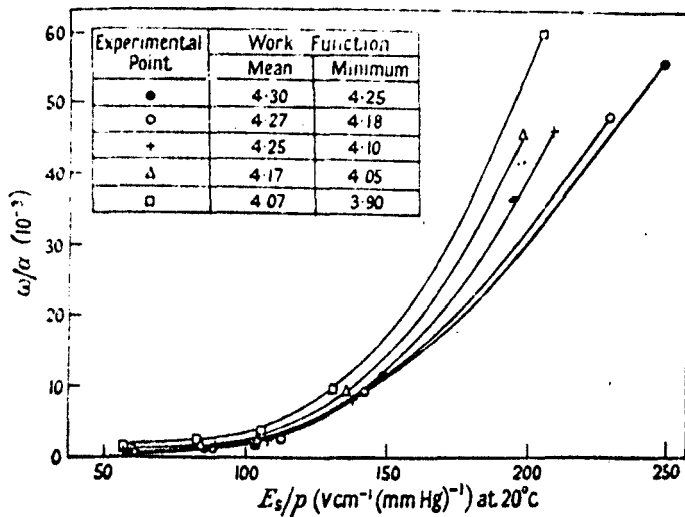
Gozna (51) initiated a FTL study in this laboratory. His FTL measurements were taken in conjunction with measurements of the work function of his cathode, and his FTL's were measured in such a way that the work function of his cathode was determined only a few moments before the discharge. He was able to establish that the cathode work function influenced V_g very considerably, and since the passage of a discharge alters the work function of an evaporated metal film cathode (52), this implies that discharging the gap, if repeated while the surfaces are still disturbed could result in a quite mistaken value of the percentage overvoltage being considered. This implies that the FTL will be dependent on the repetition period of the discharges. Fig 9 shows some of his results.

This curve has been interpreted in terms of the lowering of V_g , caused by the presence of positive ions formed in the previous discharge, on the cathode surface. Gozna applied a constant voltage at each discharge, but since V_g had been lowered by the previous discharge, this implies that the overvoltage varied with the repetition frequency. Immediately after a discharge, the percentage overvoltage was large, resulting in a short FTL, but as the percentage overvoltage decreased with time, the FTL increased as the repetition frequency decreased.

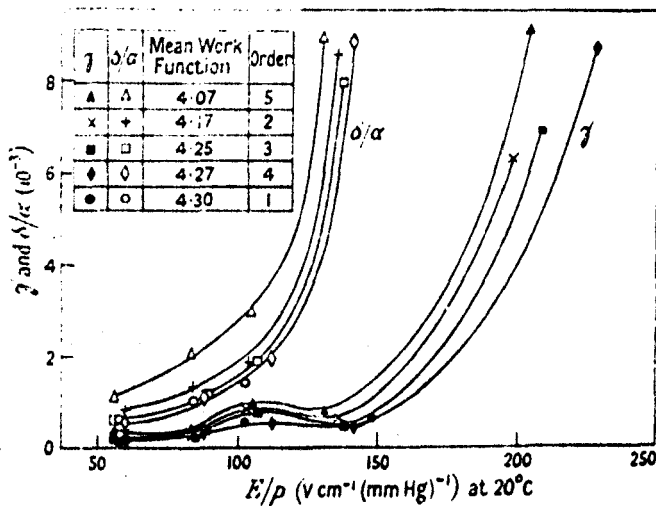
Under the conditions of Gozna's experiments, the cathode, when illuminated by a high pressure mercury lamp, returned to its original condition after about 10 sec, and this was confirmed by his FTL measurements, which show that the FTL's were constant if the repetition period were of the same order of time.

Gozna used extremely clean experimental conditions. The use of ultra-high vacuum techniques allowed the actual metal surfaces to be laid down in the absence of the usual gas mono-layers on the electrodes. His electrodes consisted of hard glass, carefully ground and polished, onto which was evaporated a conducting layer of Au, Ag or Cu. This technique, together with the usual baking at temperatures greater than 400°C enabled a higher degree of purity to be obtained than was possible in previous investigations which were conducted using bulk metal electrodes, and involved careful polishing of the electrodes, the very polishing process of necessity introducing some impurities. Gozna's H_2 was obtained by the electrolysis of $\text{Ba}(\text{OH})_2$ solution which was then passed through two sets of palladium osmosis tubes. As a further refinement, he stored the H_2 as UH , and then obtained H_2 in his experimental tube by heating the hydride. This, however, produced no significant amendments to his previous results.

Llewellyn Jones and Jones (53) have also investigated the variation of the FTL with the work function of the cathode. They used bulk metal electrodes and hence very careful outgassing procedures had to be followed in order to remove all tarnish layers. Different cathode surfaces were then obtained by sputtering Al, Pt and Ni onto the base metal electrode as required. Unlike



ω/α plotted against E/p for cathodes of different work function.



γ and δ/α plotted against E/p for cathodes of different work function.

Fig 10

Gozna, who used the Kelvin vibrating electrode method to measure the work function, Anderson's retarding potential method was adopted with gold as the reference surface. Their electrical apparatus was basically that previously used by Morgan, and they too obtained their η_2 from UH.

By measuring the FTL's obtained with any one particular surface, and computing values of the coefficients δ/a and γ , they were able to find the dependence of these coefficients on the work function of their surfaces. They found that an increase in work function of only 0.23 eV at an E/p of $60 \text{ v}(\text{cm.mmHg})^{-1}$ had the effect of practically doubling the actual magnitudes of the secondary coefficients. Further, at an E/p of nearly $150 \text{ v}(\text{cm.mmHg})^{-1}$, about 95 per cent of the secondary action was photon action and only 5 per cent due to positive ions. This was in agreement with Morgan's earlier work. Fig 10 shows some of Llewellyn Jones and Jones results.

Thus it can be seen from this review of FTL measurements at low percentage overvoltages that it is extremely important to have an electrode system that is really clean and quite reproducible. It should also be pointed out that all the work in section 2.5 has been conducted with a tube whose gap distance was fixed during any particular experiment, and any changes in E/p were then obtained by varying the gas pressure. This has had the effect of ensuring that the same proportion of photon loss and excited atom loss occurs from the discharge area throughout the experiments.

2.6 Mathematical developments of temporal growth studies.

It has been shown earlier that there have been essentially two distinct approaches to explain the breakdown of an overvolted gap. These are the streamer

approach and the approach based on the Townsend equations of the pre-breakdown region. Mathematical theories have, of course, been developed which are based on both of these postulated breakdown processes. In this section the development of the mathematical theories associated with the Townsend mechanism will now be outlined.

Steenbeck (54) initiated the mathematical model of the breakdown process when he obtained the continuity equations which any valid solution must obey. Since there will be both electrons and positive ions moving across the discharge gap there will have to be two equations to describe these movements. These equations are

$$\frac{\partial}{\partial t} \frac{I_-}{w_-} = - \frac{\partial I_-}{\partial x} + \alpha I_-$$

and

$$\frac{\partial}{\partial t} \frac{I_+}{w_+} = + \frac{\partial I_+}{\partial x} + \alpha I_-$$

any equation which describes the current flowing as a function of time must satisfy these continuity equations, and further, they must satisfy the relevant boundary conditions for any particular set of experimental conditions. Solutions have been presented, from time to time, which have proved to be inadequate since the boundary conditions have not been sufficiently rigorous. Steenbeck considered the boundary conditions

$$I_-(0, t) = \gamma I_+(0, t)$$

and

$$I_+(d, t) = 0$$

these correspond to the electron current at the cathode ($x = 0$) at time, t , being expressed as some constant multiple, γ , of the positive ion current at the cathode; and the positive ion current at the anode ($x = d$) being equal to zero.

Bartholomeyczk (55) realised that these boundary conditions were not adequate if photon secondary action at the cathode was appreciable and he modified them to

$$I_-(0,t) = \gamma I_+(0,t) + \delta \int_0^d I_-(x,t) e^{-\mu x} dx$$

and again $I_+(d,t) = 0$

These boundary conditions are again not complete since they contain no reference to the photo-electric emission generated by the constant irradiation of the cathode with ultra-violet light. Gugelberg (56) noticed this in 1947 and thus introduced an I_0 term into the above expression for $I_-(0,t)$.

Later, Davidson (57) at Swansea, pointed out that even Gugelberg's modification was not really complete in that it takes no account of the initial distribution of charge in the gap. He has accordingly presented a full account of the breakdown process (developed along conventional Townsend principles with no mention of the development of space charges) which satisfies the continuity equations and the complete boundary conditions, thus obtaining expressions for the discharge current as a function of time. The actual equations are extremely complicated in that they use Green's functions and hence they are of little use without the resources of a computer. It is satisfying, however, to know that an apparently complete theory has been developed, if only applicable to simple gases such as hydrogen.

Davidson has also presented an approximate solution to the problem which is valid for breakdown times greater than a few electron transits. This solution is in a form which is comparatively easy (though more than a little tedious) to apply to the experimental conditions which existed during the initial part of this investigation.

In the same paper that Davidson first presented his exact solution, Dutton et al presented the results of their calculations using his approximate solution. They first postulated a value for the current which would be just sufficient to cause the voltage across the gap to collapse, and then they calculated the time required for the current to build up to this value. This time was then defined as the FTL.

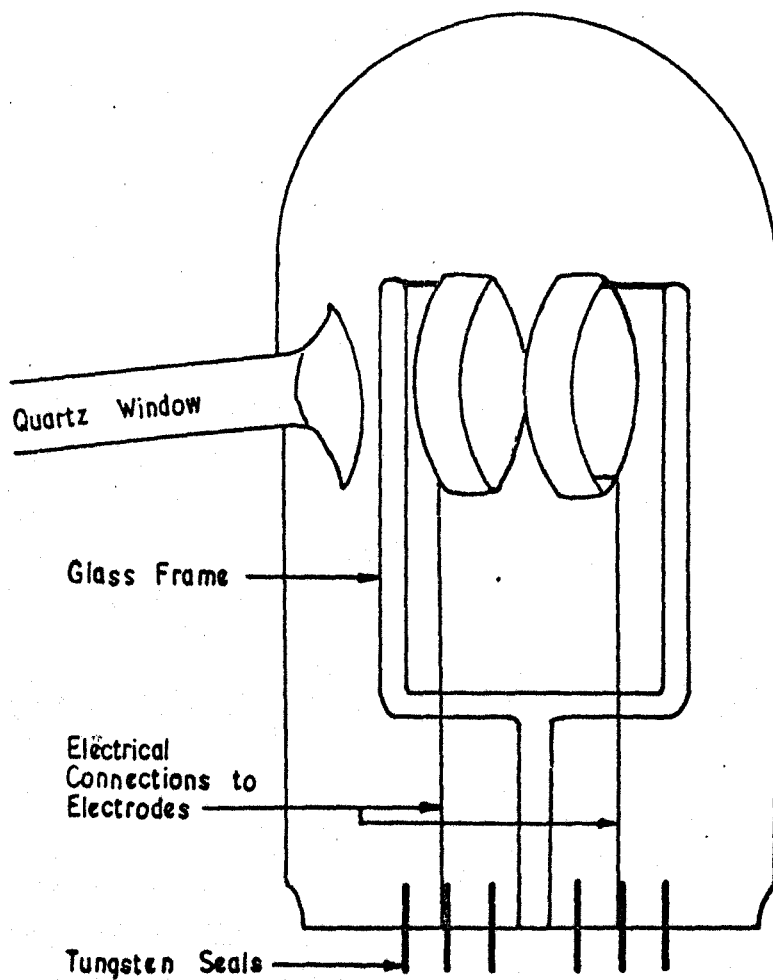
It was earlier explained that the breakdown time (i.e. the FTL) would be very dependent on the nature of the secondary processes active in a discharge, and it was pointed out that a change in the relative importance of these two secondary processes in a hydrogen discharge could change the FTL very markedly. Dutton et al assumed a certain value for the ratio δ/w , ($= \frac{\delta}{\alpha} / \frac{w}{\alpha}$) and calculated the FTL for this particular value of δ/w as the voltage across the electrodes was varied from V_g to about 2 per cent overvoltage. They thus obtained a curve showing how the FTL varied with the percentage overvoltage for a particular value of δ/w . They then repeated their calculations assuming a different value of this last ratio. In this way, the importance of δ/w on the breakdown characteristics was determined. These curves were then compared with some actual experimental curves (where the values of E/p , α/p etc. assumed in the theoretical considerations coincided with the experimentally found values) and hence by determining the value of δ/w which produced a curve which was the closest with the experimental curve, the actual relative importance of the secondary processes was found for discharges under these very low overvoltage conditions.

Dutton et al considered very different values of the final current which was taken to signify breakdown,

their values in fact varied from as little as 10^{-9} A to as much as 10^{+6} A. Such a drastic change in the breakdown current did not change the FTL vs. percentage overvoltage curve too drastically and Dutton et al say "too great a significance should not be attached to the actual value of $I_{-}(0,t)$ ".

2.7 Conclusion.

In this chapter most of the temporal growth field has been briefly considered. In the work which is discussed later in this thesis FTL's have been measured under widely varying conditions. Firstly FTL's have been measured at low overvoltages up to an E/p of $200 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$ in an attempt to determine the relative importance of the possible secondary processes at the various E/p 's and to detect any effects on the secondary coefficients of a change in the gap geometry (of a change in the ratio d/D). Secondly a study of the temporal growth under overvoltages sufficiently high to produce nano-second FTL's was made. Breakdown under these very different conditions happens as a result of very different processes. In the low overvoltage case breakdown is thought to be due to the growth of current on the Townsend mechanism of primary and secondary ionization processes; while in the high overvoltage case, it becomes apparent that such an approach alone is quite unrealistic and the space charges formed in the discharge influence very markedly the breakdown processes. In this chapter it has thus been necessary to consider the relevant work which has been conducted under both of these discharge conditions. In the following chapter the apparatus used in this investigation is described.



TUBE 1

Fig 11

CHAPTER III

DESCRIPTION OF APPARATUS

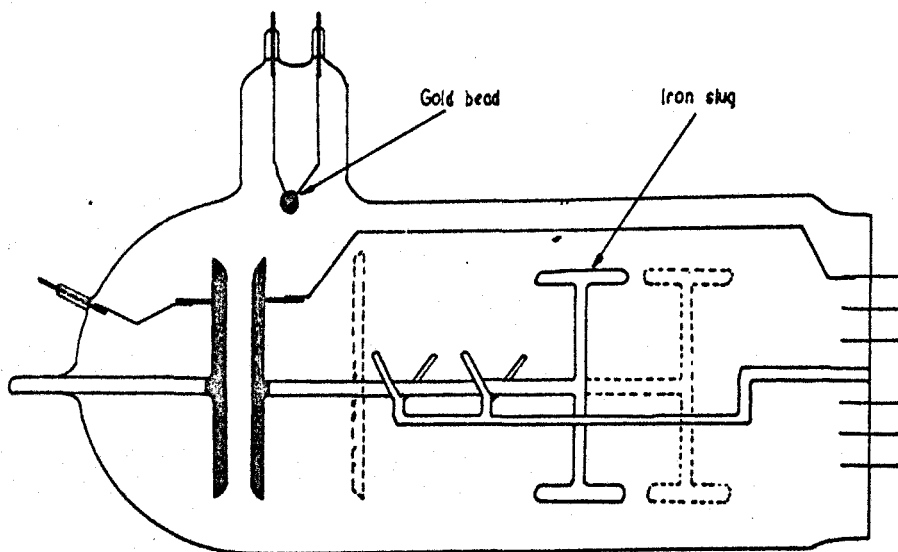
3.1 Introduction

In chapter 1 it was pointed out that two quite distinct investigations were conducted involving the breakdown of an overvolted gap. The earlier work involving overvoltages smaller than 3 per cent above V_g , presented quite different problems to those experienced in the later work with very much more highly overvolted gaps. Because they are so distinct, it is convenient to consider each investigation separately. In both this chapter where the apparatus is described, and in the following chapter where some aspects of the experimental procedure are detailed, the problems of the low overvoltage problem are first presented, followed by the special problems of the higher overvoltage breakdown.

The experimental apparatus can be conveniently divided into several distinct parts; the experimental tubes, the vacuum system and the electrical measuring equipment. These are now considered in more detail.

3.2 The experimental tubes used in the lower overvoltage breakdown experiments.

The first experimental tube was extremely simple. The electrodes were made of bulk nickel mounted as shown in fig 11 on a glass frame. The inter-electrode distance was set by placing a machined plastic spacer between the electrodes, and then softening the glass frame until the electrodes were resting on the spacer. In this way also the electrodes were set quite parallel to each other, though it must be realised that once set, the gap distance could not then be altered. U.V. light was



TUBE 2

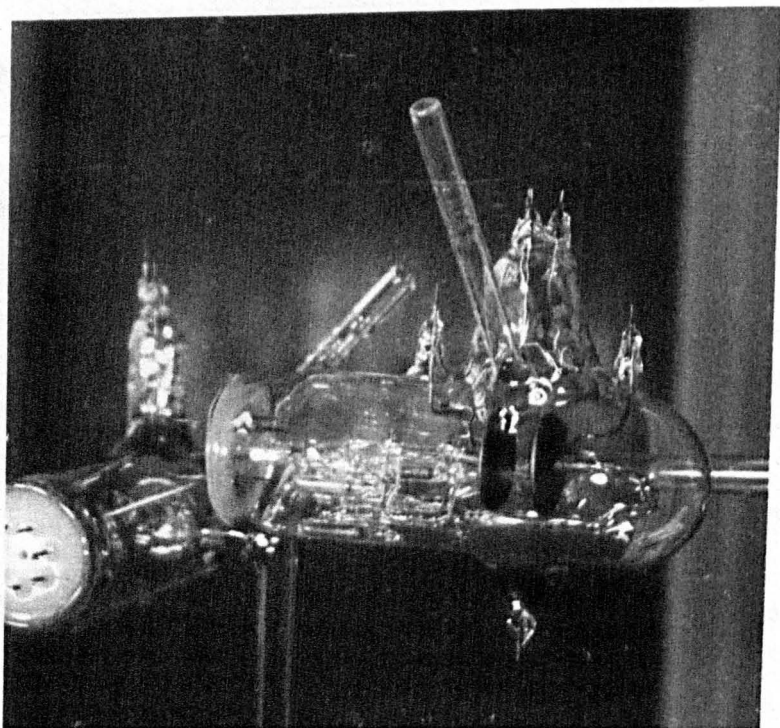
The dashed lines indicate the positions of the electrodes and iron slugs when the gold bead is evaporated. In this position the inter-electrode distance is at a maximum. The quartz window and the tubing connecting experimental tube to manifold are not shown.

Fig 12

admitted on to the cathode at glancing incidence by using a quartz window. Electrical connections to the electrodes were made via nickel wires spot welded onto the back of the electrodes, which were run to the commercial pinch that had seven tungsten rods sealed into it.

Tube 1 was used to establish the basic techniques of FTL measurement, and hence any undesirable effects of using a tube with bulk metal electrodes and a fixed electrode distance were relatively unimportant at that stage. All the later tubes used in this part of the investigation did not have bulk metal electrodes, and all had a continually variable gap distance.

Fig 12 is a diagram of tube 2, which is essentially the same as all the rest of the tubes which were used for the low overvoltage experiments. The electrodes were made of glass with a conducting layer of gold evaporated onto them. Hard glass rods were melted down and the resultant molten material flattened on a carbon block. With care, a disc like shape could eventually be obtained whereupon one area of the disc near the centre was heated particularly strongly and a tungsten rod pushed almost completely through. This tungsten rod was to serve as the electrical connection to the actual electrode surface. After careful cooling, the glass disc was carefully ground using several grades of carborundum powder in rotation, so that a smooth face was obtained with the tungsten rod exposed. At this stage sharp corners existed at the edge of the disc, and these had to be ground off to prevent any concentration of the field occurring at these sharp points. This grinding was successfully accomplished by mounting the electrodes in a lathe and gently applying a small piece of



Tube 3

Fig 13

carborundum stone to the sharp corners.

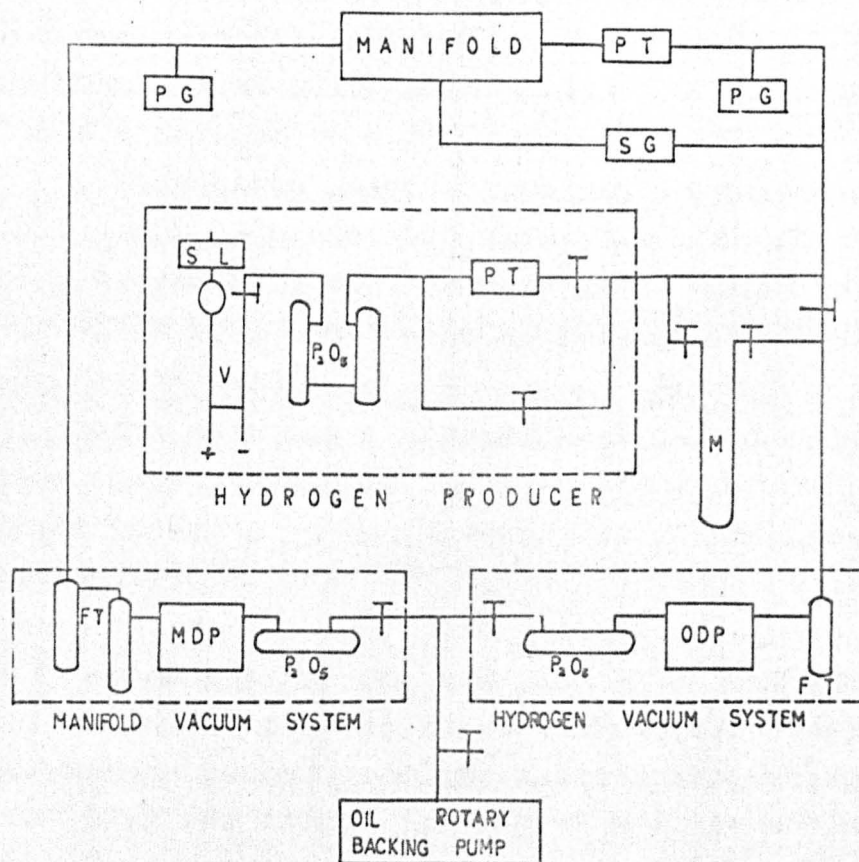
In all these later tubes the cathode was fixed, and it was the anode which was moved in order to change the gap distance. In tube 2 the cathode was fixed to the end of the tube, while the anode was attached to the pinch at the other. This method of mounting seemed to be convenient at the time, though great difficulty was experienced in setting the electrodes parallel to each other, and thus in all the later tubes both electrodes were connected via glass rods to the pinch. This second method implies, however, that a glass rod has to pass between the electrodes and the envelope wall, but this can be conveniently accommodated by blowing out a part of the envelope. In all these tubes the electrodes were mounted centrally so that they were a uniform distance away from the envelope walls.

The moveable anode mechanism was the same in all these later tubes. A glass rod attached to the rear of the anode rested on a cradle which was attached to the pinch. Two iron slugs, sealed in a small glass envelope were attached to this rod, thus allowing the electrode to be moved by an external magnet.

Electrical connections were made to the cathode in all the tubes by a tungsten seal which was situated behind the cathode. This extra tungsten seal introduced a further potential leak to air, but it was considered worthwhile as it avoided any troubles which may have arisen, due to field distortion, on passing a connecting wire from the cathode, past the anode, to the commercial pinch. Electrical connection to the anode was made via the pinch (except in tube 3 where another tungsten seal was used as shown in fig 13).

The conducting layer on the electrode surface of tube 3 was barium, while that for tubes 2, 4, 5 was gold. The barium was obtained from commercial barium getters, two getters being positioned to deposit barium onto each electrode. The getters were heated by passing a current through them from a "regavolt", which could give a current of 10A at a potential difference of 20V. The gold for the other tubes was obtained from some fine gold wire, a convenient amount of which had first to be prepared in the form of a bead. The procedure was to wind about 6" of the wire lightly onto a tungsten frame, which was mounted inside a glass envelope through which hydrogen could be passed continuously. A steady stream of hydrogen was passed through the tube, emerging from a very fine hole, and after some minutes the hydrogen emerging from this hole was lit and the speed of the stream adjusted to produce a jet about 1" high. A steadily increasing current was then passed through the tungsten wires via the "regavolt" until the gold had become molten and clung to the tungsten frame as a small bead. The current was passed until the gold surface was clear and free from any visible impurities, and then the bead was carefully cooled. The gold bead thus obtained was mounted at a suitable position midway between the two electrodes as shown in fig 12. Connections for heating the bead were via the usual tungsten seals.

Charge build up on the glass walls of the envelope could have produced undesirable field distortion, and hence it was arranged to have an electro-static screen around the electrodes. This screen was created automatically when gold and barium were evaporated, contact to earth being achieved by a tungsten seal and a small piece of tungsten wire which was sprung, to



MDP Mercury Diffusion Pump

ODP Oil Diffusion Pump

M Manometer

V Voltmeter

SG Spiral Gauge

PG Penning Gauge

SL Soda Lime

FT Freezing Trap

T H E V A C U U M S Y S T E M

Fig 14

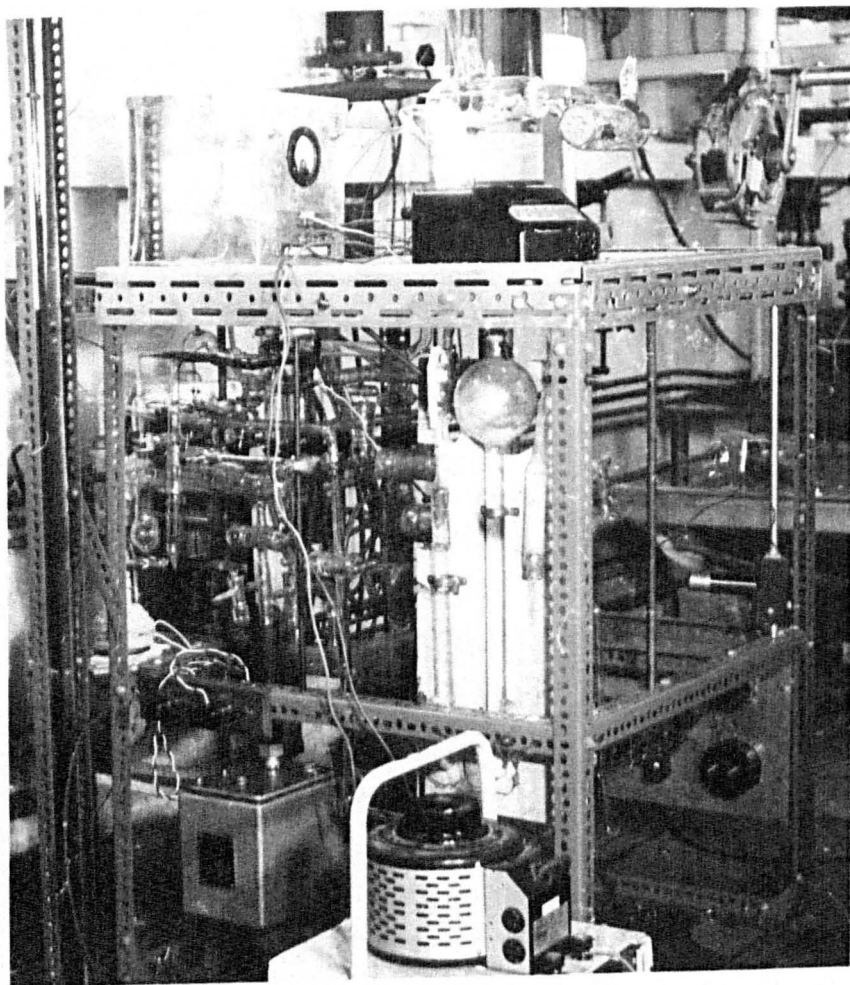
ensure that contact was always made with the gold on the envelope.

3.3 The Conventional vacuum systems used for both investigations.

Two distinct conventional vacuum systems were required, one to evacuate the experimental tubes and the other to evacuate the hydrogen producing apparatus. Both systems were constructed of hard glass and both used the same shaft driven oil rotary backing pump. The complete vacuum system and hydrogen producing apparatus is shown in fig 14.

The manifold system used a Jencon's 3 stage mercury diffusion pump, while the hydrogen vacuum system used a single stage oil diffusion pump. In actual fact, this "oil" diffusion pump was a glass pump designed for use with mercury, but as it was considered desirable to avoid using freezing traps on the hydrogen side, and since use of mercury could well have resulted in an amalgam forming on the palladium thimbles it was decided to attempt to use the pump filled with oil. This proved to be very satisfactory. Edward's silicone fluid (704) was used which has a vapour pressure of less than $5 \cdot 10^{-7}$ mm Hg at 15°C . Freezing traps containing liquid nitrogen and phosphorous pentoxide (P_2O_5) traps were used as shown in fig 14.

These vacuum systems could pump down to pressures of the order of 10^{-6} mm Hg (the mercury pump a little lower than "oil" pump). Pressures in the range 10^{-3} to 10^{-6} mm Hg can be conveniently measured using a Penning gauge. The Penning gauges used in this investigation, were constructed in the laboratory, and consist essentially of a nickel anode on either side of which is a nickel



General view of apparatus while
Alpert pump was in operation.

Fig 14b

circular plate cathode, the cathodes being about a centimetre in diameter and positioned about a centimetre apart. A magnetic field of 600 oersteds was applied perpendicularly to the plates by means of a small permanent magnet. The gauges were positioned just beneath the asbestos top of the frame between the vacuum systems and the manifold as shown in fig 14.

Great care was taken to ensure that grease could not possibly contaminate the experimental tubes, and hence no grease taps were used on the manifold vacuum system, other than the one tap between the backing pump and the diffusion pump.

While results were actually being taken, the experimental tubes were left on the manifold for some weeks at low pressures. Frequent letting down to atmospheric pressure was not required, and hence it was not considered worthwhile to invest in metal taps to be used between the manifold and the manifold vacuum system. Instead a number of "glass constrictions" and "breakers" were constructed, which could be used to isolate the manifold from the pumps (by closing a constriction in the glass tubing) and, when required, the manifold could be opened to the pumps again (by smashing the thin glass at one of the breakers with an iron slug). The iron slug, sealed in a glass envelope in order to prevent the metal outgassing, was moved by a magnet from one breaker to another as required.

The hydrogen vacuum system was separated by a grease tap from the hydrogen producer, and beyond this grease tap the hydrogen system was separated from the manifold by a palladium thimble and a spiral gauge. These will be discussed more fully in section 3.5.

3.4 The ultra-high vacuum system used for both investigations

The ultra-high vacuum system was situated on the manifold, and its purpose was to reduce the residual gas pressure in the manifold from about 10^{-6} mm Hg to pressures less than 10^{-8} mm Hg. The essential parts of this vacuum system were a getter tube and a Bayard-Alpert ion pump. The getters were made of barium contained on a nickel frame, the frame being spot-welded on to a nickel rod, and positioned on the manifold in a position so that it was convenient to fire them with a radio-frequency eddy current heater. The getters were able to reduce the residual gas pressure in the experimental tubes from 10^{-6} mm Hg to 10^{-7} mm Hg.

The Bayard-Alpert ion pumps (58) were usually made in this laboratory and can reduce the residual pressure in the experimental tubes to less than 10^{-8} mm Hg. The grid of the ion pump (which can also be used as a pressure measuring gauge) was made from tungsten and was wound on a copper former, such that there were about 6 turns per centimetre, every turn being spot welded into position. The collector wire was made from very thin tungsten wire, which was sometimes etched to reduce its thickness still further. Two tungsten filaments were included inside the glass envelope, so that if one filament was to burn out the ion pump would not be rendered useless. The positive ions are removed from the system by becoming embedded in either the glass envelope or in the ^{collector} ~~grid~~, actually more ions become attached to the glass than became attached to the ^{collector} ~~grid~~ (59). Electrical contact is made to the collector and filament through the 7 pin commercial pinch, and to the collector wire by a tungsten seal through the top of the envelope.

Towards the end of this investigation it was decided to invest in commercial Bayard-Alpert gauges; they were physically smaller, though they had the same essential features of those described above.

3.5 The hydrogen producer and the measurement of hydrogen pressure

Hydrogen was obtained by the electrolysis of a solution of barium hydroxide. The oxygen side of the voltameter was separated from the atmosphere by a tube containing sodium carbonate, which prevented any carbon dioxide reaching the hydroxide, where it would have formed a precipitate of barium carbonate. The hydrogen was dried by allowing it to stand for some hours over two phosphorous pentoxide traps, and was then passed into the manifold by heating the two palladium thimbles shown in fig 14.

The palladium thimbles consist of a palladium tube, closed at one end, the open end of which was sealed onto a piece of platinum tube; the platinum tube was then sealed into some lead glass which was sealed via a graded seal to a hard glass tube leading directly to the manifold. The palladium absorbs hydrogen very readily, and so during an actual experiment, the palladium thimble heaters were kept on. The heater on the first thimble consisted of a coil around a hard glass tube which enclosed the palladium tubes. This type of heating is now considered undesirable (60), since it can result in the hard glass outgassing and contaminating the hydrogen. The second thimble was heated by a wire coil surrounding the palladium tubes.

The hydrogen pressure in the manifold was measured by using a spiral gauge and an oil manometer. The

spiral gauge was connected across the second palladium thimble, and was arranged to give a zero reading when the pressure on either side of the thimble was the same. The oil manometer measured the pressure of the hydrogen on the side of the palladium thimble away from the manifold. Thus in order to be able to record the pressure in the manifold, it was necessary to heat the palladium for some hours (usually about six hours was required) until the spiral gauge reading was zero, the pressure on both sides of the thimble was the same, and hence the oil manometer reading gave the pressure of hydrogen in the manifold. In this way the pressure could be measured with an oil manometer, without the oil being able to contaminate the experimental tubes.

3.6 The voltage source and the voltage measuring apparatus for the lower overvoltage breakdown experiments

In order to measure ETL's a source of static backing potential is required, and, in addition a source of pulse voltage. The static backing potential was supplied by a bank of about eight 120V dry batteries connected in series, a precise voltage adjustment being obtained by using a 500 Kohm potentiometer across one of the batteries. In this way it was quite possible to obtain potentials which differed by as little as 0.1V.

The cathode and the screen of the experimental tube was earthed, the anode thus being at a positive potential with respect to the earth. This potential difference was measured with the aid of a voltage divider consisting of a chain of ten calibrated 1 Mohm resistors in series with a 10 Kohm resistor. A conventional potentiometer (Cropico P3) was used to measure

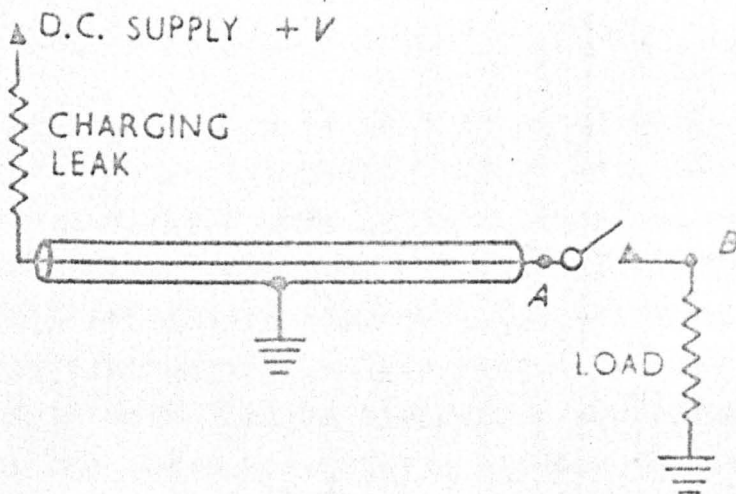
the potential drop across the 10 Kohm resistor, whence, by multiplication by the appropriate factor, the total potential difference could be calculated.

The pulse voltage was obtained from a Solartron pulse generator. This is a convenient instrument to use in that it can supply pulses of amplitude from 10v to 100v at intervals of 10v, with a continuously variable pulse length from zero up to 250 μ sec. The voltage pulses can be triggered externally, or internally, at repetition rates of from 50 per second up to 10,000 per second. The output voltage, however, was not accurately set at 100v, and its true value was conveniently measured by using a 545 A Tektronix oscilloscope. The rise time of the Solartron was of the order of 0.1 μ sec.

The probe which was most frequently used with the oscilloscope attenuated the incoming signal by a factor of 10, and was effectively a 10 Mohm resistance shunted by a 10 pF capacitance. It was thus necessary to connect a small capacitor between the probe and the electrodes of the experimental tube, in order to avoid a voltage drop across the probe, when measurements were being taken.

3.7 The experimental apparatus used for the higher overvoltage breakdown experiments

The apparatus used for this part of the investigation was basically that which was developed by Dawson (47), whose experiments were briefly considered in section 2.4. The conditions in this experiment were such as to produce FTL's in the nano-second region. For such short times, it was extremely convenient to obtain the voltage pulse which was to be applied to the experimental gap, by discharging a charged co-axial



Basic circuit producing the pulse

Fig 15

cable by using a very fast switch. The experimental tube was small enough to be positioned along the inner conductor of the co-axial cable without creating too much of a discontinuity to any voltage pulses travelling along the cable.

In order to discuss the experimental apparatus, it is useful to consider first some of the properties of the co-axial cables used in this investigation. These cables have the property that the velocity of propagation of any waves along the line is independent of frequency. This is essential if voltage pulses are to be transmitted along the line without distortion. The cable can be said to have a certain parallel capacitance per unit length, C , and a certain series inductance per unit length, L . The characteristic impedance, Z_0 , of such cables can be shown to be purely resistive and equal to $(L/C)^{1/2}$, and the time delay per unit length, T , of the cable can be written as $(LC)^{1/2}$.

Consider a length of the co-axial cable charged to a voltage V through a high resistance, as in fig 15. On closing the switch a square pulse of amplitude $+V/2$ passes across the switch, and a pulse of amplitude $-V/2$ flows back along the line. Both of these voltage pulses will be affected by any discontinuities along the cables and it is useful to consider three such discontinuities: (i) the pulse may feed into a resistive load, of magnitude Z_0 , (ii) the pulse may arrive at an open circuit and, (iii) it may be presented with a short circuit between the inner and outer conductors. In case (i) the wave is completely absorbed, there being no reflected wave at all. At the open circuit (ii) the wave is completely reflected, so that the polarity of the current is reversed,

while the polarity of the voltage remains unchanged. This means that the voltage of the reflected wave is added to the voltage of the incident wave (producing voltage doubling), while the current of the reflected wave cancels the current of the incident wave, to give zero total current in the cable. In case (iii), the short circuit, the reflection now takes place with the voltage polarity being reversed, and the current polarity remaining unchanged.

Considering again fig 1.5 it can be seen that the voltage pulse of amplitude $-V/2$ which travels back along the line, on reaching the high charging leak resistor, R (R much greater than Z_0 , i.e. high enough to be effectively an open circuit), is reflected as described above, the result being that a pulse of amplitude $+V/2$ and width $2T_1$ (l = length of the cable), is discharged across the switch. This is basically the method which is used to produce both of the voltage pulses which are required for the experiment. The details of the actual circuit employed will now be considered in more detail.

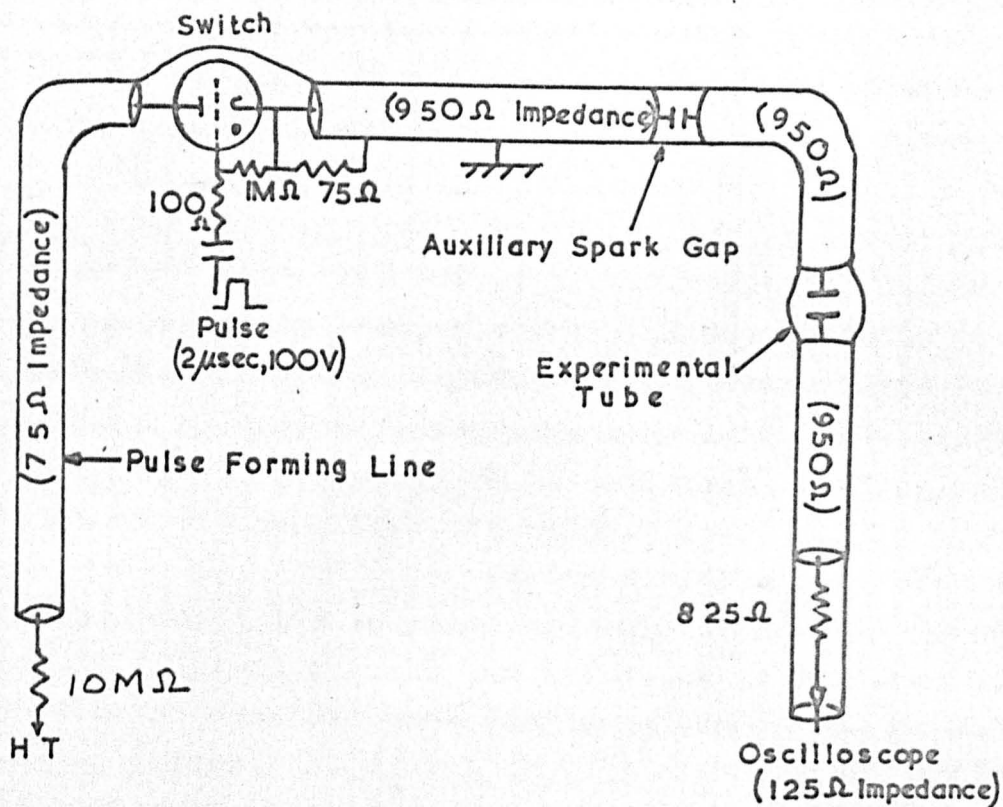
In order to produce a practical cable circuit there are essentially three requirements which must be satisfied. First a suitable length of cable is required which, when discharged, will produce a square pulse of the desired length. Secondly, a very fast switch is required, in order that a square pulse may travel along the cables, and lastly the experimental tube must be of a suitable size, and be carefully positioned, so that it doesn't present too much of a discontinuity in the cable circuit.

The length of cable which is required to produce a given pulse length is very dependent on the

on the particular cable which is used. Some cables with a straight wire as an inner conductor, have thus a low value of L , and hence T is somewhat small also. Other cables, however, have a helically wound inner conductor with a higher value of L , and hence an increased value of T . Using these latter cables thus results in a shorter length of cable being required to produce a pulse of a given length. For this investigation pulses of up to 200 nsec were required, and using 75 ohm television cable a length of about 12' was required, while using a Transradio 950 ohm cable (RG-35A/U) this length was reduced to about 3'. During this investigation both kinds of cable were used as the pulse forming line and both were found to give acceptable results.

There are many varieties of switches which may be employed to discharge the charged co-axial cable. Dawson used a hydrogen thyatron (Mullard XH3-045) which was found to operate fairly satisfactorily when triggered by a small commercial pulse generator (EMI Type 1). The same method was used in this investigation, though it was found to be desirable to increase the triggering pulse length from the small pulse generator to 2 μ sec, which was easily accomplished by attaching about a 200 yd. length of 75 ohm television cable to the pulse generator. This cable was then discharged by using a very fast relay switch which was wetted with mercury, thus producing very fast rise times in the emergent pulse, which was then applied to the grid of the thyatron.

In chapter 2 it was pointed out how desirable it is in gas discharge investigations to prevent too



CIRCUIT FOR HIGH OVERVOLTAGE

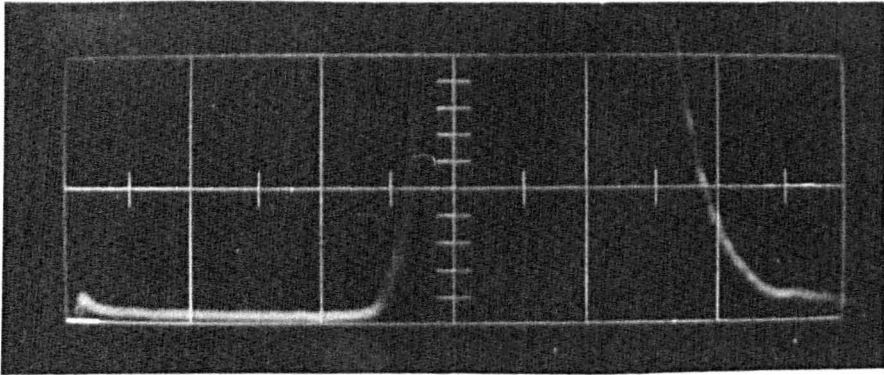
EXPERIMENTS.

Fig 16

high currents flowing which might damage the electrode surfaces. It is thus extremely desirable to use high impedance cables, so that any currents which flow when a cable at a given voltage is discharged is kept to a minimum. For this reason, as well as for the high value of T , the Transradio cable No. RG-65A/U was found to be particularly suitable for this investigation. When a length of television cable (with a lower impedance) was used, as the pulse forming line, the pulse had, of course, to be fed into a 75 ohm load in order that maximum power was transferred and no undesirable reflections were set up; this was conveniently achieved by having a resistance of about 75 ohm placed across the inner and outer conductors of the 950 ohm cable, into which the pulse was being fed.

On discharging the cable using the hydrogen thyratron as just described, a pulse with a rise time of about 20 nsec was obtained. This is too large when FTL's of the same order are to be measured, and it was found that positioning a small air spark gap along the cable had the effect of reducing the rise time to about 5 nsec. These auxiliary spark gaps are frequently pressurised, but since a rise time of less than 5 nsec was quite acceptable for this experiment, normal air pressure was used in this investigation.

The cable from the cathode of the experimental tube led through an 825 ohm resistor to the 125 ohm impedance input of the 519 Tektronix oscilloscope, thus presenting a load to the pulse of 950 ohm (= the characteristic impedance of the cable). The electrode system is essentially a capacitance of value a few pF's and hence a small displacement current flows



Typical Trace Obtained at High Overvoltages.

Fig 17

through the oscilloscope, charging up the gap, when the pulse arrives at the anode. This displacement current was found to be quite adequate to trigger the oscilloscope, thus allowing the ensuing current flowing across the gap to be displayed on the oscilloscope. The FTL was defined as being the time between the peak of the displacement signal on the scope and the first observable current rise (corresponding to a current of just less than 10^{-2} A). The complete circuit is shown in fig 16 and a typical trace in fig 17.

The experimental tube was much simpler than those used in the earlier experiments. The electrodes were made of bulk nickel. The tungsten rods leading from the electrodes to the outside of the tube being kept as short as possible and the whole tube being enclosed in a co-axial arrangement constructed by Dawson, in an attempt to avoid any unwanted reflections of the incident voltage pulse. From gas discharge considerations, it is imperative that the ratio gap distance (d) to electrode diameter (D), i.e. d/D be kept as small as possible. This implies that for a given d , D must be very much larger (up to $10.d$ for really uniform fields); this, however, is not really possible since the whole tube size must be kept as small as possible. Further, a high D , and a too small d , might very well increase the gap capacitance to a value such that the displacement current would be many times greater than the current flow which is taken as signifying breakdown. It is thus necessary to compromise to a certain extent, and D was usually equal to about $2.d$.

In this chapter the apparatus used in the whole investigation has been briefly described. In

the following chapter the basic techniques employed in measuring FTL's are presented, while the remaining chapters consist of a discussion of the experimental results obtained in this investigation.

CHAPTER IV

EXPERIMENTAL PROCEDURE AND CALCULATION OF THE FTL

4.1 Introduction

In this chapter, some indication is given of the actual experimental procedure. The preparation of the experimental tubes is described, and the techniques of measuring FTL's at both the low and the very much higher overvoltages are also outlined. Lastly the methods used to calculate FTL's are outlined briefly.

4.2 Preparation of the experimental tubes

It was a lengthy procedure to prepare the experimental tubes up to the point when hydrogen was first admitted. The manifold vacuum system pumped the tubes down to a pressure of the order of 10^{-5} mm Hg, and then the whole manifold assembly was covered with an oven and baked at 450°C for up to 48 hours, while still pumping with the backing pump and the diffusion pump. This procedure was essential in order to outgas all the glassware associated with the experimental tubes. The pressure increased, of course, when the oven was first switched on, but, the system being free of leaks, eventually fell lower than 10^{-6} mm Hg. Liquid nitrogen traps were always used between the pump and the manifold, to prevent any mercury vapour entering the experimental tubes.

After this first preliminary baking of the manifold assembly, it was then necessary to outgas the metal parts, and in order to do this adequately they had to be heated to temperatures much higher than 450°C . For

metal parts such as bulk metal electrodes, Bayard-Alpert pump grids, barium getters, this heating was conveniently accomplished by using a radio-frequency eddy current heater. On heating these metal parts to red heat, the pressure rose quite considerably; they were kept hot until no further gas was given off, and the pressure had returned to its earlier value of the order of 10^{-6} mm Hg. The gold bead could not be heated in this way, instead the "regavolt" passed an increasing current through the tungsten frame containing the bead, until the surface of the bead just became mobile. Great care had to be taken to ensure that the tube was quite steady during the process, since a slight jerk could have caused the bead to fall from the tungsten wire; and further, there was a risk that the tungsten rods which were sealed into the glass and through which electrical contact was made with the bead, could have become too hot and actually cracked the glass. The specially mounted barium getters in tube 3, were heated in this way by the "regavolt" to red heat and the filaments of the Bayard-Alpert pump were similarly heated.

The metal parts having been outgassed, the glassware was again baked for up to 48 hours. At this stage, the pressure in the manifold was less than 10^{-6} mm Hg, and it was necessary to seal the manifold vacuum system by carefully collapsing one of the constrictions mentioned in section 3.3. The constriction was first carefully heated, in order that any gas given off by this more intense heating would be carried away by the pump, and when the glass was eventually just at its softening point, a getter was fired. The constriction was closed and another getter fired. In order to be quite sure

that there were, in fact, no minute leaks to air, the pressure was read on the Bayard- Alpert pump, which was then switched off and the manifold left for 24 hours, after which time the pressure was again noted, and if no pressure rise was indicated the pump was left on for two or three days. The temperature of the filament was adjusted so that the ^{electron} ~~positive ion~~ current at the grid was about 5 milli-amps. After about two days the pressure should have been reduced to less than 10^{-8} mm Hg, this corresponding to minute filament currents, too small really to be read on the Cambridge micro-ammeter, requiring really an electrometer.

When the manifold was at as low a pressure as could be obtained, the gold and barium surfaces were laid down. The gold and barium were heated by using the "regavolt" as described under the outgassing procedure, though they were, of course, heated to higher temperatures when evaporation was required. It was necessary after the surfaces and electrostatic screen had been laid down, to be able to measure the distance between the electrodes, and hence it was necessary to ensure that a small window was created in the gold and barium covered envelopes. This was easily achieved by enclosing in the envelope a moveable iron slug, again sealed in a glass tube, which could be held by a magnet against the envelope where the window was required.

4.3 Sparking potential measurements

It is somewhat difficult to define the sparking potential V_s , in a way which is acceptable to all workers in the gas discharge field. In section 1.2, it was defined as the minimum voltage which must be applied in order that the gap may break down. Diffi-

culties are encountered in practice, however, in actually measuring V_g . Sometimes application of a given voltage will cause breakdown, and at others it will not, hence some workers define V_g as being the voltage which when applied across the gap causes breakdown in 40 per cent of the cases, others 50 per cent or even 100 per cent. It is apparent that this is entirely at the discretion of the investigator; such problems of definition were avoided in the lower over-voltage experiments (where a value for V_g was required) by plotting a FTL vs. applied voltage curve and taking V_g to be that voltage where the FTL tended to infinity. This was sometimes found to be convenient, though at others it was found that the FTL curves did not increase really steeply enough for a truly unambiguous definition of V_g .

The applied potential, of course, was the sum of the static backing potential (measurable to better than 0.1V) and the 100V voltage pulse (measurable only to about 3V). Variations in the applied voltage were always made by varying the static backing voltage, while the pulse voltage remained constant throughout; this implying that when V_g was clearly defined on the FTL vs. applied voltage curve (i.e. when the static backing potential part of V_g could be determined to better than 0.1V), overvoltages up to the desired 3 per cent could be applied to an accuracy of 0.1V; i.e. for voltages of the order of 600V say, an overvoltage of say 2 per cent could be applied to an accuracy better than 1.5 per cent. This was not always the case, however, and when V_g was not obtainable so precisely, the accuracy of the overvoltages was obviously somewhat less.

In the second part of this investigation at very much higher overvoltages, it was explained in section 2.4 that a static measurement of V_g had really no relevance to the experimental conditions, hence V_g was not determined at all.

4.4 FTL measurements at the lower overvoltages

The voltage applied to the experimental gap consists of a static backing voltage, V_B , and a pulse voltage, V_p , such that $(V_B + V_p)$ is greater than V_g . V_B was applied from a bank of about eight 120V dry batteries and V_p from a Solartron pulse generator. The probes of the oscilloscope were connected across the electrodes, and the voltage pulse displayed on the screen. At breakdown, the gap voltage collapsed, and hence the FTL could be easily determined as the time from the beginning of the pulse, to the moment the voltage collapsed.

The voltage pulse could be obtained from the pulse generator in different ways. The pulses could be obtained at specified repetition rates ranging from 50 per sec to 10,000 per sec, and it was also possible to apply the pulse using an external trigger. Both internal and external triggers were used during the investigation, though for most of the results, the external trigger was used. For tube 1 which was used merely to establish the techniques of measuring FTL's the internal trigger was used and the resultant breakdowns displayed on the 545A Tektronix oscilloscope. A repetition rate of 50 per sec was used and hence many pulses were seen on the screen at any given instant. This method was thus useful in order to find the range over which FTL's occurred, though it was quite useless to attempt to measure the mean FTL. There

are also serious objections to applying pulses in this way. Gozna (51) found that charge built up on the electrodes when the gap broke down, and the electrodes took times up to ten seconds to regain their original state. Application of pulses at rates of 50 per sec results in the breakdown being very dependent on these charge build-up effects, and hence for any meaningful measurements it was necessary to use an external trigger and apply the pulses about every ten seconds. This was the method used for tubes 2 to 5 inclusive.

The pulse length was continuously variable up to 250 μ sec, and since FTL'S up to about 40 μ sec were usually measured a 50 μ sec pulse was found to be quite adequate. With this arrangement breakdown currents only flowed across the gap for a few μ sec, and hence no appreciable damage was done to the electrode surfaces. The Tektronix oscilloscope No.545A was particularly suitable for measuring FTL's in the range 1.5 μ sec to 40 μ sec, since it had time base scales of 0.5, 1, 2, 5 and 10 μ sec per cm (amongst others). The oscilloscope screen had a long persistence, and hence it was convenient to measure the FTL's visually. It would be a straightforward matter to photograph the traces, but this was not considered necessary for this investigation.

The technique employed for obtaining a graph of the FTL vs. percentage overvoltages, was to set the static voltage so that $(V_B + V_p)$ was as close to V_B as possible and take between 20 and 50 readings of the FTL; the static voltage was then increased by about 2V and the FTL measured again, this process being repeated until the total applied voltage was 3 per cent above the approxi-

mate value of V_g . A graph was then plotted of these FTL's against corresponding voltages, and from this graph a value of V_g was determined as explained earlier. Having obtained V_g , the FTL vs percentage overvoltage curve was then constructed.

There is, of course, not a wholly acceptable way of obtaining the FTL corresponding to any particular applied voltage. The range of measured FTL's at times was quite considerable, and an argument can be put forward in favour of taking the mean value of the readings as being the quoted FTL, and alternatively, it can be argued that not the mean value but the reading which occurs most frequently should be the quoted FTL. In practice there is probably not too much difference between these two definitions; however, it is as well to realise that there is no overwhelming reason to accept either definition. For all the results quoted at the lower overvoltages (i.e. for the first 5 tubes) the mean of between 20 and 50 readings was taken as being the FTL.

4.5 Calculation of the FTL at the lower overvoltages

The equations used to calculate FTL's were the ones used by Dutton et al (49), and are basically Bartholomeyczk's which have been modified by Davidson. It is necessary to have values of α , w/α , w_- and w_+ corresponding to the experimental conditions.

The value of α was obtained from Fletcher's α/p vs E/p curve (61), which was obtained in this laboratory under virtually identical experimental conditions. w/α was calculated from Townsend's break-down criterion, namely,

$$1 - \frac{w}{\alpha} (e^{\alpha d} - 1) = 0$$

w_- and w_+ were at first taken from quoted values in Dutton's and Morgan's papers, though for later calculations, w_+ was taken as being 100 w_- and values for w_- taken from tables quoted by Emeléus et al (9).

The procedure adopted to calculate a FTL vs. percentage overvoltage curve at any particular E/p was as follows:

(i) Having obtained from Fletcher's results a value of α corresponding to the given experimental conditions, the value of w/α was calculated from Townsend's breakdown criterion.

(ii) Values of δ/α and γ were chosen such that:

$$w/\alpha = \delta/\alpha + \gamma$$

(iii) A particular overvoltage was considered.

In this investigation it was decided to calculate curves up to 2 per cent overvoltage, in which range w/α would be essentially constant. It was then necessary to calculate values of a constant, λ from the equation $F(d) = 0$, where,

$$F(d) = 1 - \frac{\gamma\alpha}{(\alpha - \frac{\lambda}{w_-})} \left[e^{(\alpha - \frac{\lambda}{w_-})d} - 1 \right] - \frac{\delta}{(\alpha - \frac{\lambda}{w_+})} \left[e^{(\alpha - \frac{\lambda}{w_+})d} - 1 \right]$$

where, $\frac{1}{w} = \frac{1}{w_-} + \frac{1}{w_+}$

This was a lengthy procedure and had to be achieved by successive approximation.

(iv) The value of λ obtained was inserted into the following equation,

$$I_-(0,t) = \frac{I_0 (1 - e^{-\lambda t})}{1 - (\gamma + \frac{\delta}{\alpha})(e^{-\alpha d} - 1)}$$

Where $I_-(0,t)$ was the current at the cathode at time t , which was taken as signifying that the gap had indeed broken down. The time, t , which is the FTL, is then calculated from this last equation.

It can be seen that this process is very tedious, and further, since values for w_- and w_+ are required (which have not been measured at the E/p's involved in this investigation), the results of the calculations must be interpreted with care.

4.6 FTL measurements at the higher overvoltages

With very much higher applied voltages, the FTL's were reduced by a factor of about 10^{-3} . The circuit employing high impedance co-axial cables was described in section 3.7. The current flowing across the gap was displayed on a Tektronix oscilloscope (No.519), and the FTL measured visually for most of the results, though as with the 545A oscilloscope it was a straight forward matter to photograph the traces.

As for the lower overvoltage case, some way of selecting one value, as the FTL corresponding to a given set of conditions, was required, and this time it appeared to be more meaningful to take the FTL as being the breakdown time which occurred most frequently. The conditions

for this experiment were such that breakdown could possibly have been a result of the multiplication of a single avalanche. The distribution of FTL's found was not symmetrical about a mean value, most of the FTL's being found at the lower end of the distribution, and thus taking the mean value as being the FTL would have produced a value substantially different from taking that which occurred most frequently.

The pulse forming cable was discharged about every 5 sec, by applying a triggering pulse from the commercial pulse generator to the thyatron, which was used as a switch. The results were this time plotted in the form FTL vs. E/p , the concept of V_g and over-voltages not being very meaningful under the given experimental conditions (as explained in section 2.4).

4.7 Calculation of the FTL at the higher overvoltages.

The smallest current which when flowing across the gap could have been observed on the oscilloscope was a little less than $10^{-2}A$. If breakdown had been caused by the passage of a single electron (charge q) moving across the gap without any secondary effects being active, the time, t , taken for the gap to break down, i.e. the FTL, would have been given by:

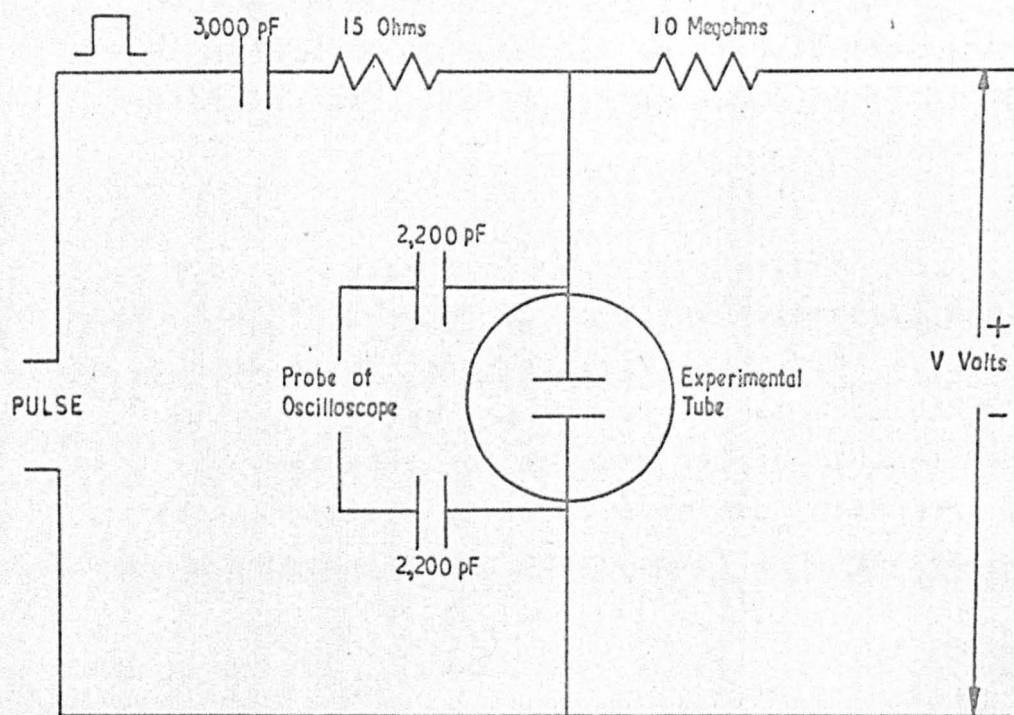
$$10^{-2} = \frac{qw}{d} e^{aw-t}$$

Assuming breakdown was essentially a primary process (this is dealt with more fully in chapter 6), then t could have been calculated if values of a and w were assumed. These values of the FTL would be very markedly altered if appreciable space charges had developed across the gap, and could be entirely misleading if the values of a and w used were not applicable under the

given experimental conditions. Thus the equation above had to be regarded with care. It did not necessarily enable the FTL to be calculated under the experimental conditions, but merely enabled a theoretical time to be calculated which would have been valid if space charge effects had not been important.

4.7 Summary

In this chapter a brief review has been given of the techniques employed to measure FTL's in the course of this investigation, and of the methods used to calculate FTL's. In the following chapters the experimental results obtained in this investigation are presented, and an attempt is made to interpret them in terms of fundamental gas discharge processes.



BASIC CIRCUIT FOR DETERMINATION OF FORMATIVE TIME LAGS.

Values of Resistance and Capacitance shown were not always used, but were slightly changed from time to time in order to produce a more square pulse across the electrodes of the experimental tube.

Fig 18

CHAPTER V

RESULTS AND DISCUSSION OF THE LOW OVERVOLTAGE BREAKDOWN EXPERIMENTS

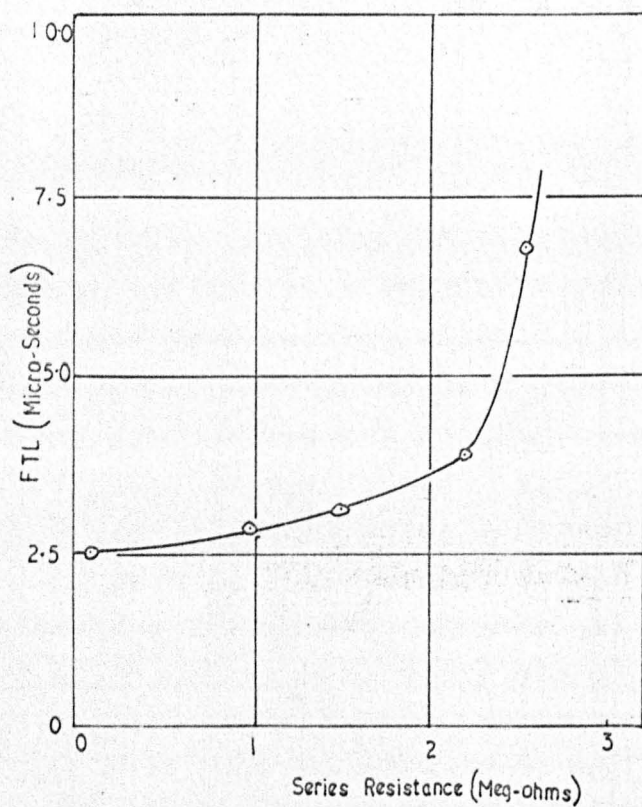
5.1 Introduction.

In this chapter the results obtained from the first five experimental tubes are presented, and an attempt made to interpret them in terms of gas discharge processes. The experiments were conducted with hydrogen in the low pressure range, which was introduced into the manifold only after rigorous pumping and outgassing procedures had been followed, which reduced the pressure in the manifold to less than 10^{-8} mm Hg. The FTL was measured, at over-voltages up to 3%, at different values of the parameter E/p , where $40 < E/p < 200 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$. From these experimental curves, and with the aid of a mathematical analysis, attempts have been made to determine the relative importance of the two possible secondary processes which could have been active in the considered discharges.

5.2 Preliminary results from tube 1.

Tube 1 was very simple, having bulk metal electrodes at a fixed separation of 0.57 cm. The usual vacuum techniques were used, but owing to the nature of the electrodes, pressures as low as 10^{-8} mm Hg could not quite be obtained.

Considerable time was initially spent in developing the techniques of measuring FTL's. The pulse from the pulse generator had a rise time of 10^{-7} sec, but care had to be taken for the pulse which appeared across the gap to rise so quickly. Fig 18 shows the circuit which was



VARIATION OF FTL WITH SERIES RESISTANCE

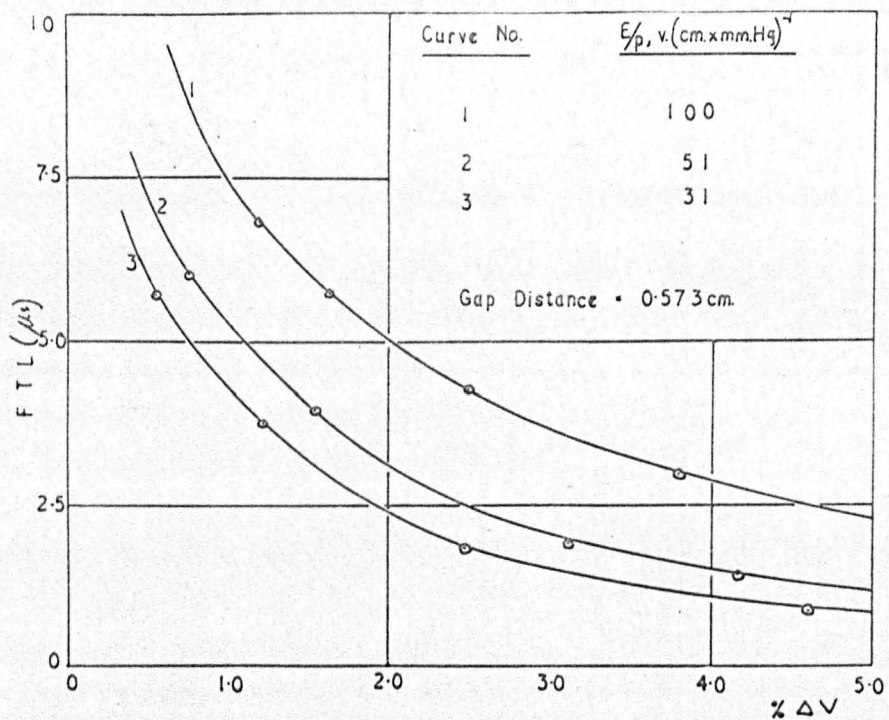
Fig 19

frequently used, though some of the values shown were modified from time to time, in order to improve the pulse shape.

An interesting result of this stage of the investigation was the confirmation of Gozna's work (51), that the series resistor in the backing potential circuit influenced the breakdown of the gap. This is important, since it implies that if the circuit parameters are shown to affect the FTL then the results are not very meaningful unless the complete circuit is specified. From fig 19 it can be seen that the FTL was essentially constant whenever the series resistor was less than about 2 Mohm.

A further interesting matter was the variation of the FTL with the pulse voltage. The procedure used to measure FTL's was described in chapter 4; essentially a backing voltage (V_B) and a pulse voltage (V_P) were applied to the experimental gap, where ($V_B + V_P$) was greater than the sparking potential V_g . Pulse amplitudes between 10V and 100V could be obtained from the pulse generator, and it was apparent that with the smaller pulse voltages, a greater backing voltage was required, and hence the initial pre-breakdown current was increased, with the result that the FTL could perhaps be altered. Pulses of 100V, 50 V and 10 V were used and the usual FTL vs. percentage overvoltage curves obtained for overvoltages up to 6%. The curves obtained were virtually identical, the FTL's from all three curves being within 5% of each other, for a given overvoltage. For the tubes 1 to 3 inclusive, a pulse amplitude of 105V was used (and for tubes 4 and 5 a pulse of amplitude about 16V was used).

Pulses could be obtained from the Solartron pulse generator by means of an external trigger, or they could be triggered internally at rates varying from 50 per second



FTL ν $\% \Delta V$ CURVES OBTAINED USING
 TUBE 1 AND A REPETITION FREQUENCY OF 50 per SECOND.

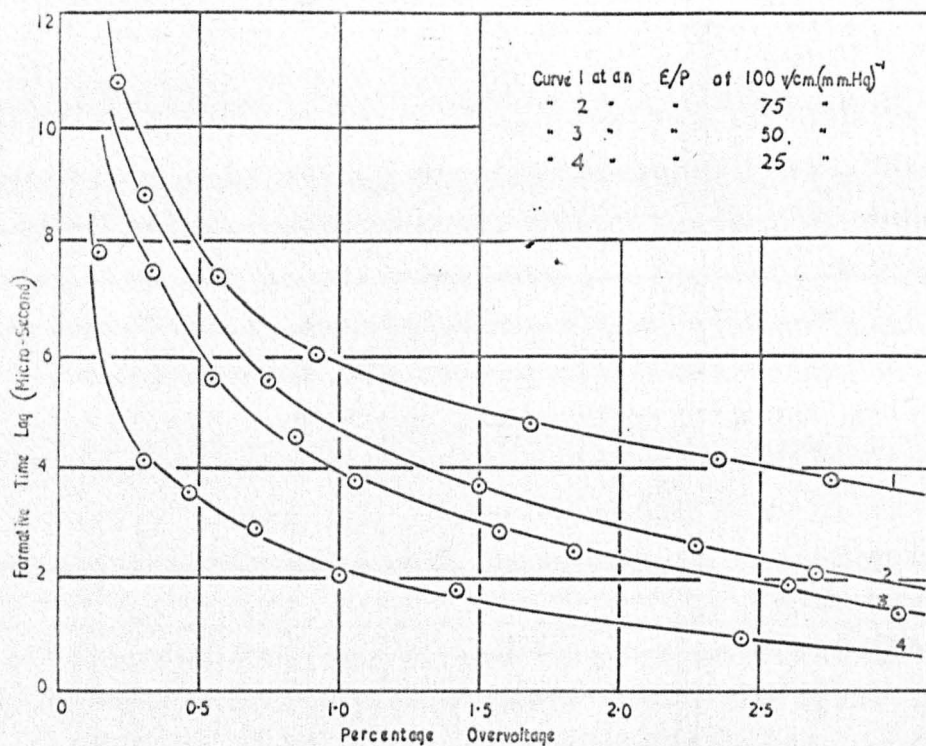
Fig 20

to 10,000 per second. Initially it was more convenient to have a signal always on the oscilloscope, and hence a repetition frequency of 50 per second was used. This procedure was quite adequate to observe any trends. Fig 20 shows some results which were obtained for different E/p_0 's, where p_0 is the gas pressure, p , reduced to 0°C . E/p_0 was altered by varying the gas pressure, the gap distance, d , remained fixed, of course, at 0.57cm throughout. In the range of E/p considered, as E/p was increased, the FTL increased for a given percentage overvoltage. This is in agreement with all previously published results in hydrogen.

Gozna found (51), however, that if the pulse repetition period was less than about 6 sec, the FTL was altered, owing to a build up of charge on the cathode surface reducing the sparking potential, and hence effectively reducing the FTL for a given percentage overvoltage. This suggested that in order to obtain meaningful results it was necessary to use the external triggering facility of the pulse generator.

The external trigger was initially applied from a battery and a mercury switch, but this was unsatisfactory as it proved to be difficult sometimes to trigger the oscilloscope to show breakdown. This difficulty could be avoided by using the oscilloscope's provision for displaying only one sweep, the trigger for the pulse generator coming from the oscilloscope at the moment the oscilloscope was primed to receive the pulse. This procedure resulted in a single pulse being displayed on the screen every time the appropriate control was used.

A further set of results was taken with tube 1 using the external trigger with a repetition period of at least 10 sec. From fig 21 it can be seen that their shape is essentially that of those in fig 20. If only the general



TUBE 1. FORMATIVE TIME LAG v PERCENTAGE OVERVOLTAGE CURVES

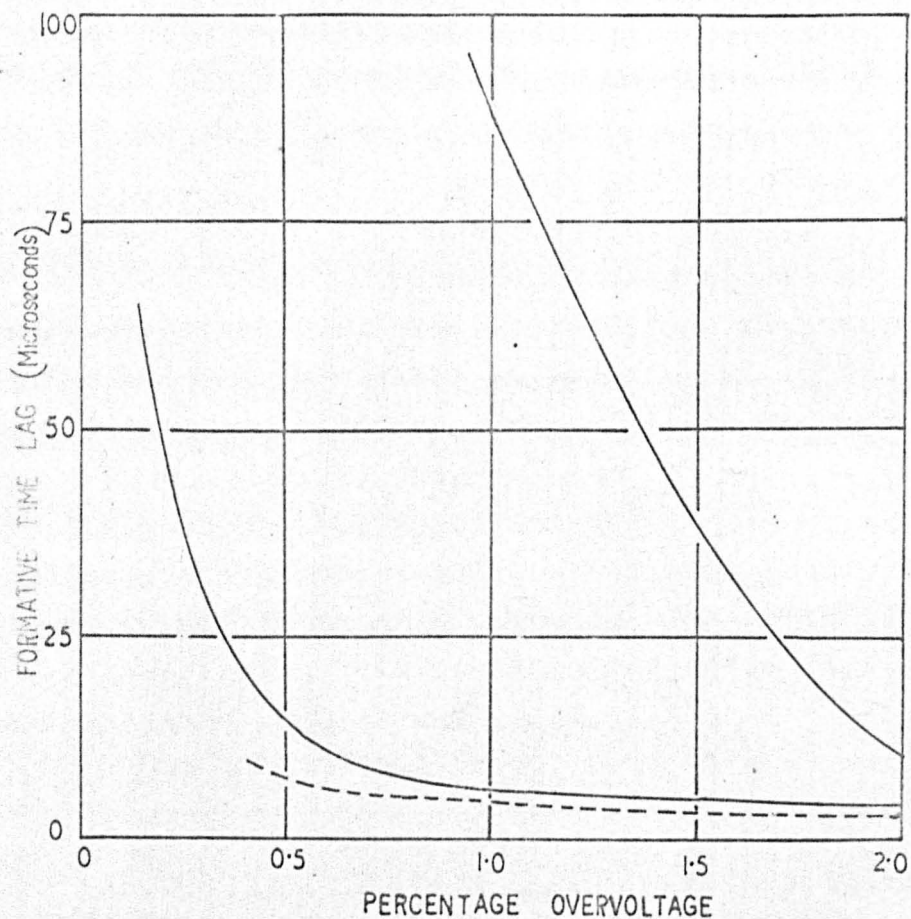
Fig 21

variation of the FTL with overvoltage is required then it is quite satisfactory to use the internal triggering of the pulse generator; however, for the results to have some real meaning, it is essential that the external triggering facility is used in order to avoid the current building up, under the action of an unspecified degree of charge build-up on the electrode's surfaces.

The FTL's obtained under a given set of conditions, displayed a substantial scatter (a standard deviation of ~ 6 , at 1% overvoltage) as was only to be expected from a study of Morgan's work (50). Workers at Swansea overcame this problem of tarnish layers on their bulk metal electrodes by running a glow discharge between them for many hours, the result of the continual ion bombardment being to remove the last traces of impurities from the cathode. Since tube 1 was only to serve as a preparatory tube for the principal tubes having evaporated metal electrodes, it was decided not to attempt to reduce this scatter, but rather to take the FTL as being the mean of about 50 breakdown times.

5.3 Mathematical analysis of the results from tube 1.

In chapter 4, the principal steps in the calculation of the FTL, using Davidson's approximate theory were outlined. The actual value of the FTL obtained using this theory, can be altered a little by varying the magnitudes of some of the constants which appear in the expressions. A value has to be assigned to the magnitude of the current which on passing across the gap causes the voltage to collapse, and the FTL will be altered as this current varies. Dutton et al (49) chose values ranging from 10^{-9} A to 10^{+6} A; such a wide range of the postulated breakdown current did not, in fact, alter the calculated FTL very



Solid lines are curves obtained by using Davidson's approximate expressions. The upper curve is calculated assuming that the ratio $\left(\frac{E}{P_0}\right) = \frac{85}{1}$ is 1, and in the lower curve that $\frac{E}{P_0}$ is $\frac{9}{10}$. The dashed line shows an actual experimental curve obtained with tube 1.

These curves are for Hydrogen at an E/P_0 of 85 volts/cm.(mm.Hg).

Fig 22

substantially. Actually the factor $I_0/I_-(0,t)$ appears in the expression, and this was taken as being 10^7 for the present investigation.

Two values of the ratio photon secondary coefficient to generalized secondary coefficient (i.e. two values of $\frac{\delta}{\alpha} / \frac{w}{\alpha} = \frac{\delta}{w}$) were considered. These were 1 and 9/10. The results obtained are shown in fig 22. It can thus be seen that this analysis indicates that the very predominant secondary process was the photo-electric process at the considered E/p of $70 \text{ V}(\text{cm. mm Hg})^{-1}$, a result in general agreement with Morgan's work.

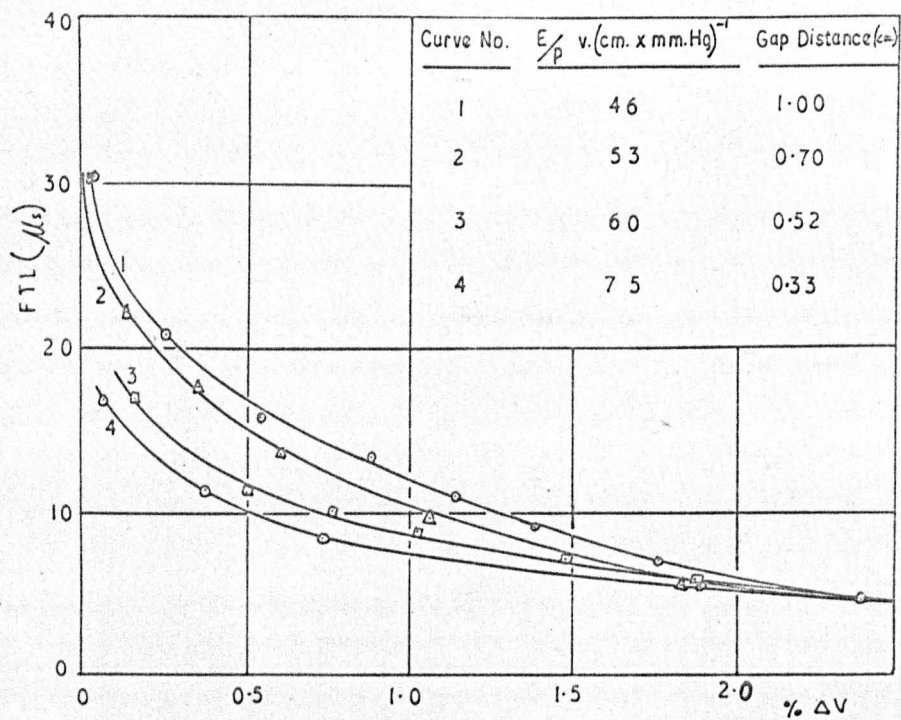
5.4 Summary of results from tube 1.

Tube 1 was an extremely useful tube. It was used primarily to develop the techniques of measuring FTL's, and to investigate just how the circuit parameters influenced the FTL measurements. A mathematical analysis indicated that the predominant secondary action at an E/p of $70 \text{ V}(\text{cm. mm Hg})^{-1}$, was photon action at the cathode. The results were obtained under conditions where the ratio of gap distance to electrode diameter (d/D) was of the order $\frac{1}{3}$, which is not small enough to claim uniform field conditions, and it was decided that subsequent tubes should have much better gap geometries and also variable gap distances. The following sections in this chapter consist of the results obtained with tubes having evaporated metal electrodes and variable gap distances, and a discussion of these results.

5.5 Results from tubes 2 and 3.

These experimental tubes have been described in some detail in chapter 3. It was hoped that with ultra-high vacuum techniques, used in conjunction with evaporated film electrodes, the scatter in breakdown times would

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F.T.L v. $\% \Delta V$ FOR BARIUM TUBE AT 18.5 mm.Hg PRESSURE

Fig 26

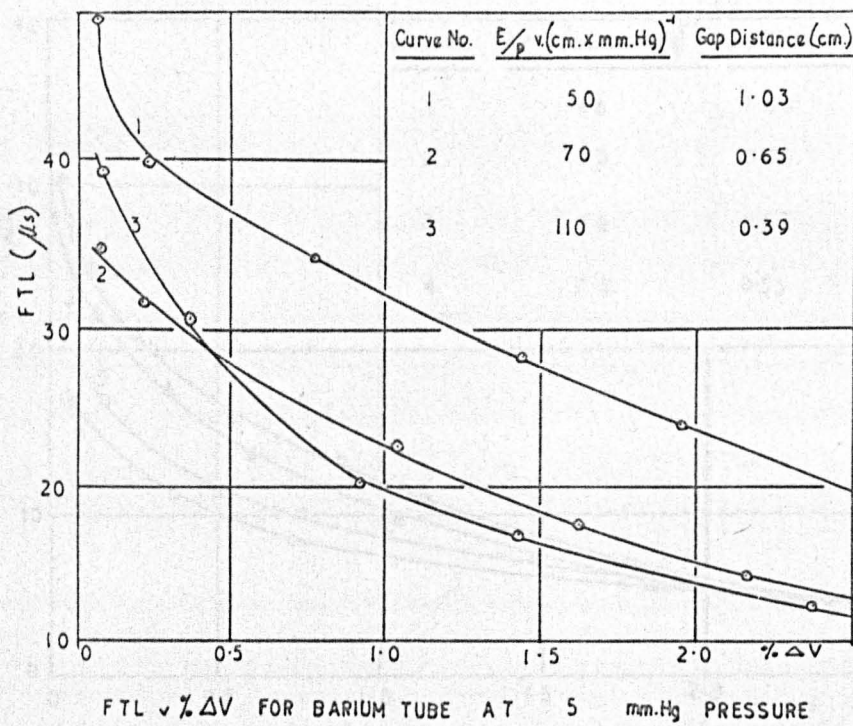
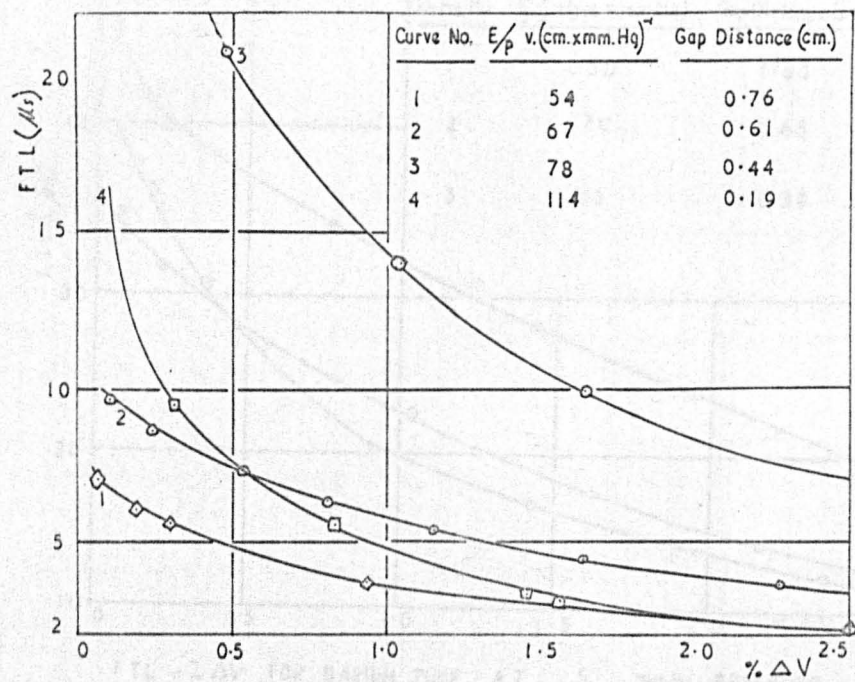
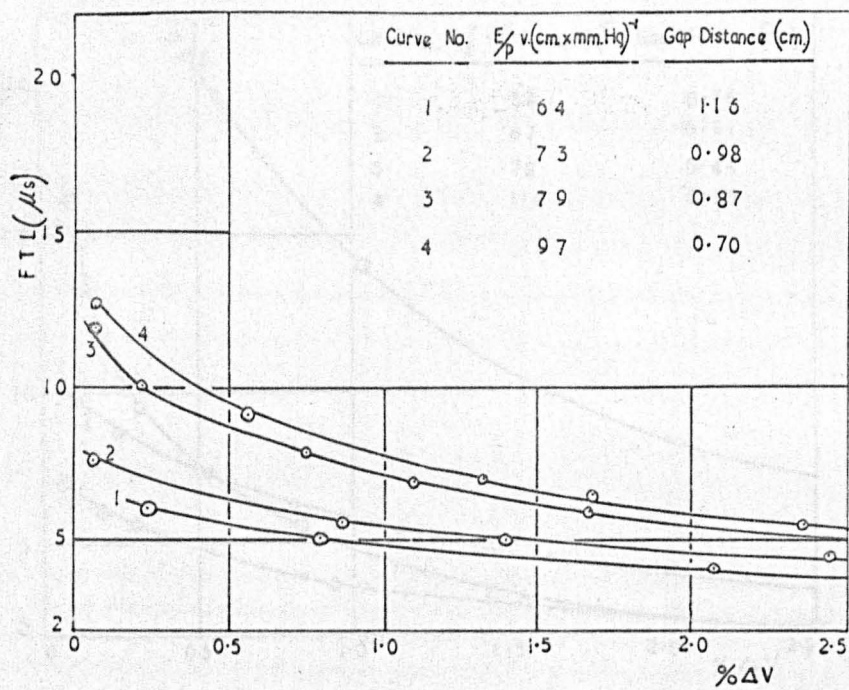


Fig 25



FTL v $\% \Delta V$ FOR GOLD TUBE AT 18.5 mm.Hg PRESSURE

Fig 24



FTL v % ΔV FOR GOLD TUBE AT 5 mm.Hg PRESSURE.

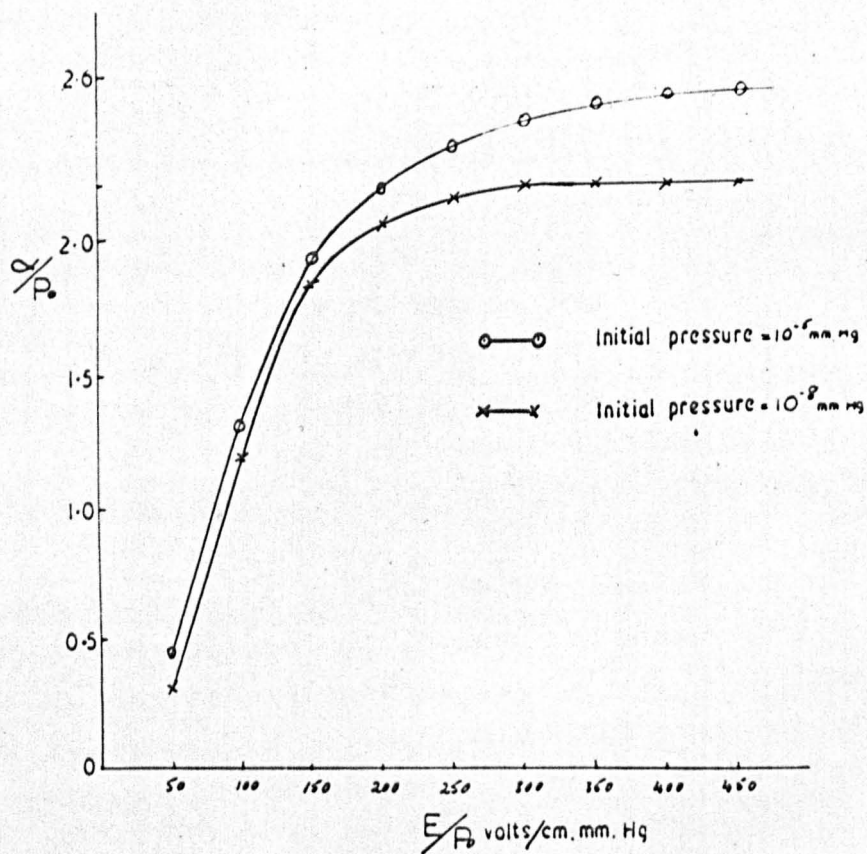
Fig 23

be substantially reduced. Further, it was hoped that the electrostatic screen around the electrodes would result in a more uniform field across the gap.

Tube 2 had gold, and tube 3 barium, evaporated onto the glass substrates. When the barium was first laid down, at a residual gas pressure of less than 10^{-8} mm Hg, it appeared as an opaque layer on the electrodes and the glass envelope, giving a mirror like sheen. The introduction of hydrogen, however, resulted in this opaque layer of barium suddenly becoming transparent. This effect has been observed frequently in this laboratory with getter tubes. Maddison (60) measured the change in the work function of the barium surface as its appearance changed, and found that the work function increased from 2.54 eV to 3.42 eV, both these values being somewhat smaller than the work function of the gold surface which was of the order of 4.7 eV.

Tube 2 was of better construction in that it was possible to vary d easily, from 0.1 cm to 1.2 cm. Such ease of movement of the anode, and such small gap distances could not be obtained with tube 3 owing to the glass covered iron slugs which were attached to the rod from the anode, being too far away from the glass envelope, thus necessitating the use of larger magnets to vary the gap distance.

It was decided to measure the FTL as a function of the percentage overvoltage for a range of E/p 's, but this time a set of results could be obtained at a given pressure, E/p being altered by changing the gap distance. At each selected value of the gap distance, the FTL was measured for various voltages (up to about 3% overvoltage), and from these curves the FTL vs. percentage overvoltage curves constructed as mentioned in chapter 4. This procedure was



Fletcher's α/p vs. E/p Curve For Hydrogen

Fig 28

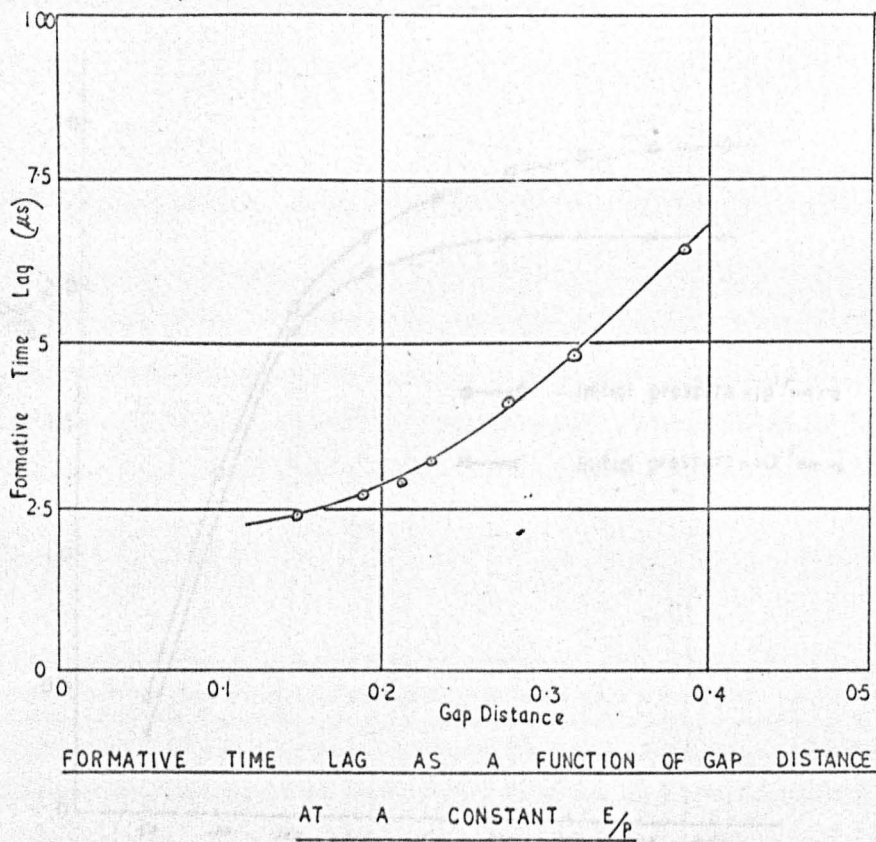


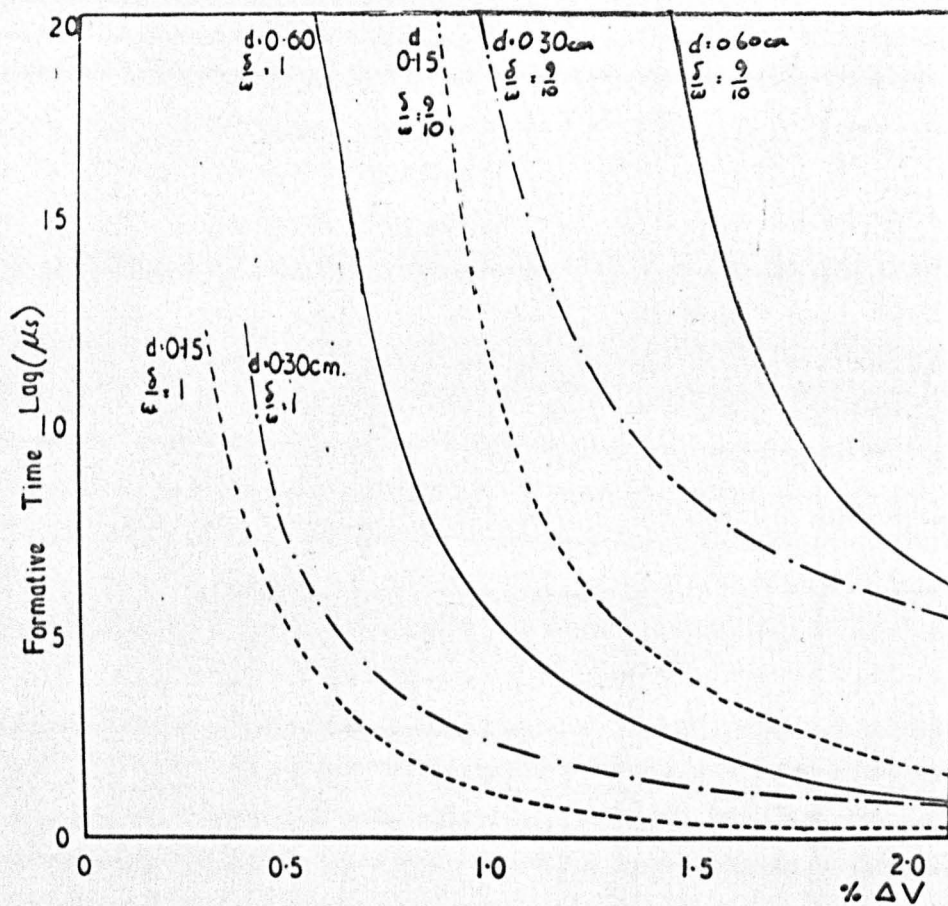
Fig 27

repeated for 4 gas pressures ranging from 6 mm Hg to 27.4 mm Hg. Some of these results are shown in figs 23 to 26. The repetition period was always greater than 6 sec. The circuit was as shown in fig 18, except that tube 2 had a series resistor in the backing potential circuit of 22 Mohm, while tube 3 had a series resistor of 4 Mohm.

An attempt was also made to investigate how the FTL depended on the gap distance, at constant E/p , pd and overvoltage. An E/p of nearly $70V(\text{cm.mm Hg})^{-1}$ was chosen, but it was not possible to keep both E/p and pd exactly constant as p and d were altered. Actually pd was maintained constant and E/p varied by about 5% from one end of the curve to the other. Fig 27 shows the curve which was obtained.

5.6 Mathematical analysis for tubes 2 and 3.

Theoretical curves, shown in fig 29, were constructed for different gap widths, assuming two distinct ratios of the photon coefficient to the total secondary coefficient (i.e. two values of the ratio $\frac{\delta}{\alpha} / \frac{w}{\alpha} = \delta/w$), at an E/p of $70V(\text{cm.mm Hg})^{-1}$. The gap widths considered were 0.6 cm, 0.3 cm and 0.15 cm and the ratios of δ/w considered were 1 and 9/10. Fletcher's α/p vs. E/p curve shown in fig 28 was used to calculate α 's, as his investigation, conducted in this laboratory, was performed under very similar experimental conditions, and his results were considered the best available. Values of electron and positive ion drift velocities in hydrogen at the E/p required are by no means very plentiful, and following Llewellyn Jones and Jones (53) the positive ion drift velocity was taken to be 10^{-2} times the electron drift velocity. The latter velocity was obtained from tables quoted by Emeléus et al (9).



Theoretical FTL Curves

Fig 29

5.7 Discussion of results from tubes 2 and 3.

The experimental curves obtained at pressures of 5 mm Hg and 18.5 mm Hg, shown in figs 23 to 26 are difficult to interpret, since the FTL is dependent on a number of factors. If it is assumed that the electrode diameter is always much greater than the gap distance, then the FTL's for a given E/p and overvoltage, would be expected to decrease, as the gap distance was reduced. In practice, however, a decrease in gap distance implies that the ratio gap distance to electrode diameter (d/D) changes. As the gap distance increases, the loss of photons from the gap increases, and hence the magnitude of the photon secondary coefficient would be expected to decrease. Such a reduction in the photon coefficient, δ/α , implies that the generalized secondary coefficient, w/α , is also reduced. This effect has been reported in both hydrogen and mercury vapour in this laboratory (61,62). The FTL is dependent on the magnitudes of the two secondary processes, and as the magnitude of the coefficient of the faster process (δ/α) decreases while that of the slower process (γ) remains unchanged, the FTL will be expected to increase as the gap distance increases. In addition to these two effects on the FTL as the gap distance changes, for a given gap distance and electrode diameter, and for a given overvoltage, the FTL has always been found to increase with E/p . These three factors have to be considered when attempting to interpret the results shown in figs 23 to 26.

The relevant experimental curves in figs 23 to 26, do not coincide exactly with any of the theoretical curves shown in fig 29. At the very small overvoltages, the calculated FTL's are substantially greater than the measured values. It was not possible to obtain consistent FTL's greater than about 20 μ sec with these two tubes. Sometimes

larger FTL's were observed, but such behaviour was not readily reproducible and at the next discharge, say, the gap could well not break down at all. This suggests that the value evaluated for the sparking potential, V_s , could be a little too high, and thus the real overvoltages could perhaps be a little higher than those shown in figs 23 to 26. The uncertainty in evaluating the sparking potential is discussed more fully in the next section. The magnitudes of the FTL's at an E/p of $70 \text{ V}(\text{cm.mmHg})^{-1}$, suggest that the very predominant secondary process was the cathodic photon secondary ionization process. Breakdown curves for higher E/p 's will be discussed when considering the results from tube 4 in the following section.

From fig 27 it can be seen that at an E/p of $70 \text{ V}(\text{cm.mm Hg})^{-1}$ at 2% overvoltage, a decrease in the gap distance from 0.3 cm to 0.15 cm reduced the FTL by 3.5 μsec . The theoretical curves show that the same decrease in gap distance produce the same reduction in FTL if 90% of the secondary action was photon action (i.e. $\delta/w = 9/10$), and if all secondary action was photon action, then the decrease would be 1 μsec . The actual decrease found experimentally will be the result of two factors, namely the reduction in the gap distance itself, and the consequent improvement in the gap geometry. In this case, d/D changes from $1/10$ to $1/20$, not a very significant change, and hence it is to be expected that the decrease in the FTL would be almost wholly due to the decrease in gap distance itself. This then suggests that the positive ion secondary process is active at an E/p of $70 \text{ V}(\text{cm.mm Hg})^{-1}$, though the photon process accounts for up to 90% of the secondary action.

It is apparent that the FTL's obtained with tube 3 (with barium electrodes) are greater for a given E/p and overvoltage, than those found with tube 2 with gold

electrodes). Gozna found (51) that for a given E/p and overvoltage, the FTL was reduced when lower work function surfaces (such as silver and copper) were used, this implying that an increase in magnitude of the secondary coefficients is associated with a reduction in the cathode work function. Jones and Llewellyn Jones (53) also investigated this effect, and found that a reduction in cathode work function of 0.23 eV had the effect of nearly doubling the magnitudes of both secondary coefficients. It would thus be expected that the FTL's obtained with tube 3 would be less, for the same E/p and overvoltage, than those found with tube 2. There are, however, differences in the experimental arrangements for the two tubes. The series resistors in the backing potential circuits were different, but from the results of section 5.2 the difference does not seem to be sufficient to appreciably alter the FTL. The gap geometry was much poorer in tube 3 (the electrode diameter, D , was 2.5 cm in tube 3, and 3.5 cm in tube 2), and thus it is to be expected that the FTL will be increased for a given E/p and overvoltage with tube 3, because of the increased photon loss. The factor just mentioned might be sufficient to account for the differences between the two tubes, but because of the uncertain nature of the electrode surfaces of tube 3, the discussion of the results which follows in this chapter, is mainly concerned with the results from tube 2.

In addition to plotting the FTL's in the manner previously considered, an attempt was made to investigate the relationship between the FTL and the gap distance, d , at constant E/p and p.d, with tube 2. Fisher and Bederson (36) found that there was a linear relationship between

these two variables. In this preliminary investigation the relation was found to be nearly linear for gap distances between 0.2 and 0.4 cm, but its slope increased as the gap distance was increased. This increase of slope at the high gap distances could perhaps be a feature of the change in gap geometry as the gap distance was changed. At the larger gap distances, d/D increases, and hence more photons are lost from the discharge gap, thus causing a reduction in the cathodic photon secondary action and consequently an increase in the FTL.

It was decided that it would be worthwhile to investigate further the relationship between the FTL and the gap distance. The curve obtained for tube 2 was only a preliminary curve, there being two factors acting together which resulted in a decrease in FTL as the gap distance was decreased at a constant E/p and pd , namely the reduction in the gap distance itself, and the consequent change in the gap geometry. In an attempt to determine the FTL vs. gap distance relationship when the gap geometry was maintained constant (i.e. constant d/D), five tubes were constructed having different electrode diameters ranging from 1.8 cm to 4.7 cm. Using these five tubes would have enabled five points to be plotted on a FTL vs. gap distance curve for any selected gap geometry. Unfortunately, owing to leaks which could not be traced, three of the tubes could not be used, and of the two which were used, useful results were only obtained with tube 4, reproducible values not being attainable with tube 5. The results from tube 4 are discussed in the following section.

5.8 Discussion of the results from tube 4.

Tube 4 had an electrode diameter, D , of 1.8 cm and was the smallest of the five tubes constructed as a set, to investigate the FTL vs. gap distance relationship. The

standard deviation of the FTL's obtained with the first three tubes was quite high, and it was thought that this could well be a result of a slight inconsistency in the amplitude of the pulses. In order to reduce any such effects, the pulse voltage, V_p , was reduced from 105 V to 16 V. The electrical circuit was of the same form as shown in fig 18, the pulse being led in through a 2,200 pF capacitor and a 15 ohm resistor, while the series resistor in the backing potential circuit was 2.2 Mohm. Such an arrangement reduced the standard deviation at 1% overvoltage to ~ 3 , when using a pulse repetition period greater than 6 sec.

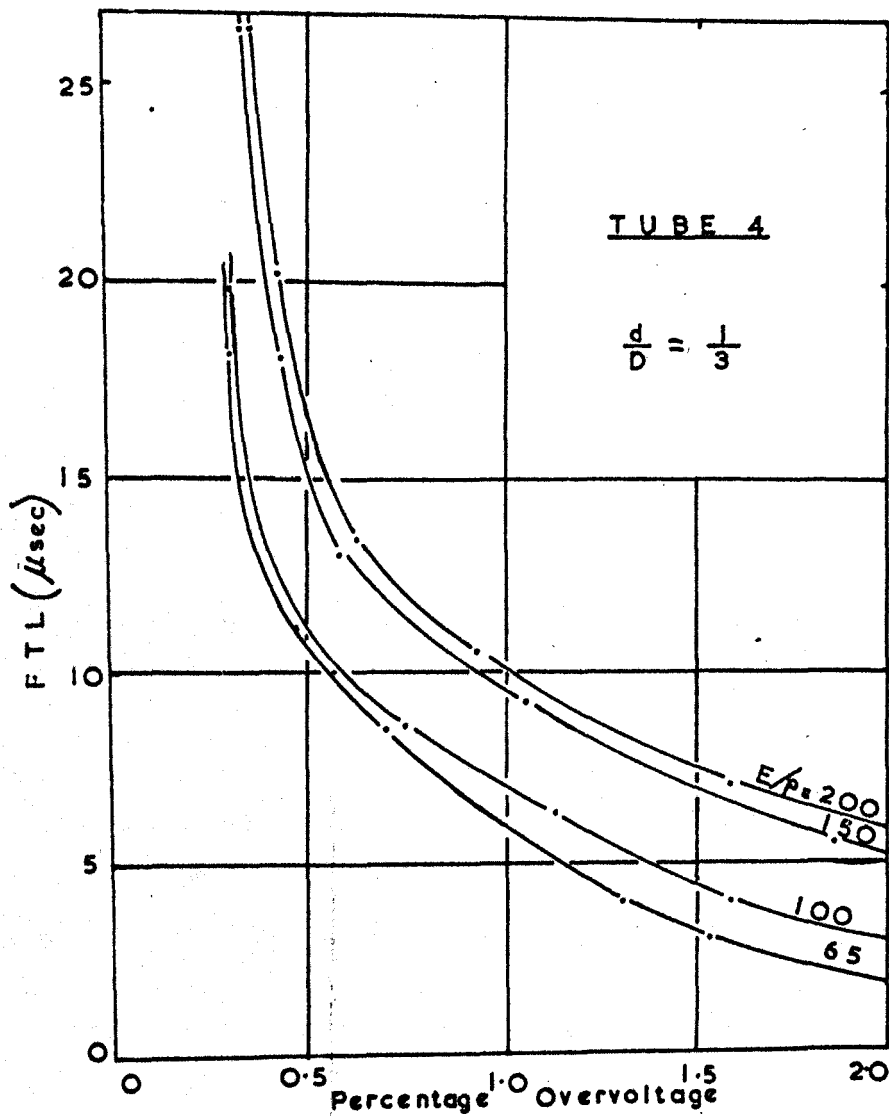
As before, a series of FTL readings was taken for a number of voltages, and from these an estimate made of the sparking potential, V_s . In tubes 1 to 3 this value of V_s was evaluated simply by estimating from a graph of FTL vs. $(V_B + V_p)$, at which value of the total applied voltage, the FTL tended to infinity. This was unsatisfactory since the whole presentation of results, and indeed the conclusions which are obtained from them depend very critically on the sparking potential. From a graph of the FTL vs. $(V_B + V_p)$, it is seen that the increase in FTL near the sparking potential is virtually exponential, and hence it is possible to write, to the first order that:

$$(V_B + V_p) = V_s e^{bt}$$

where b is some constant, and t = the FTL. If then the FTL vs. $(V_B + V_p)$ curve is plotted on semi-logarithmic paper, and two points taken on the curve near to breakdown, V_s can be evaluated from the relation:

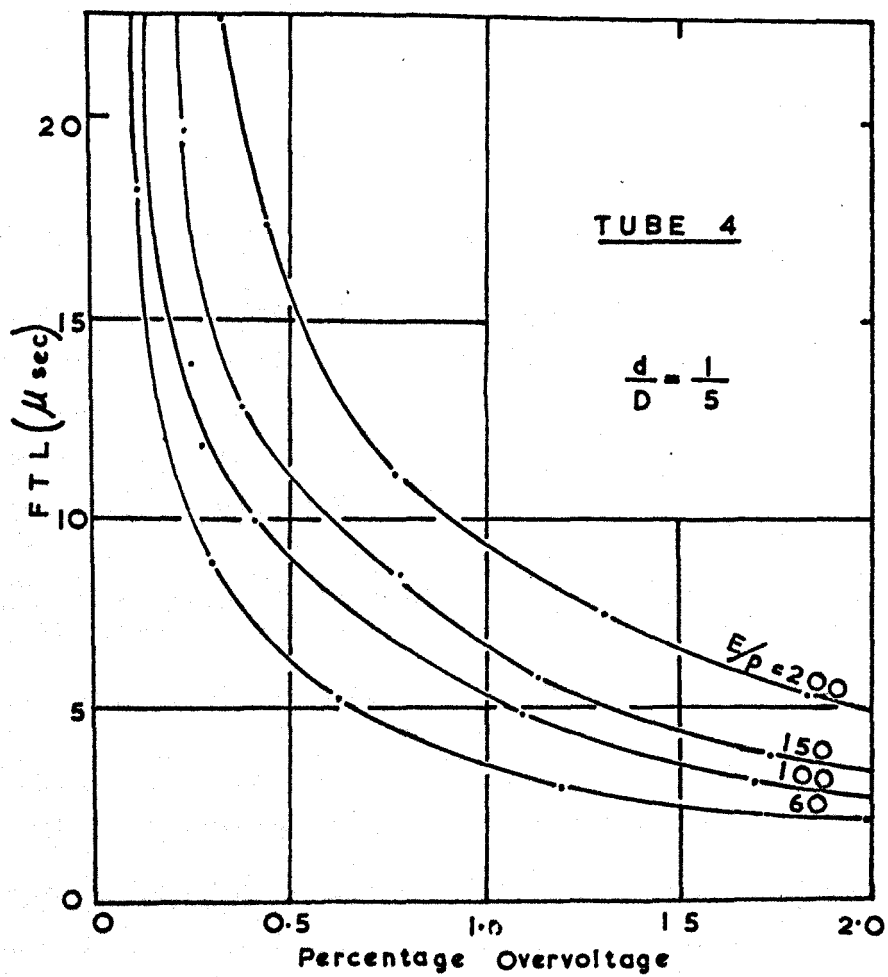
$$\ln V_s = \frac{(t_1 \ln V_2 - t_2 \ln V_1)}{(t_1 - t_2)}$$

where V_1 and V_2 are the values of $(V_B + V_p)$ at the two



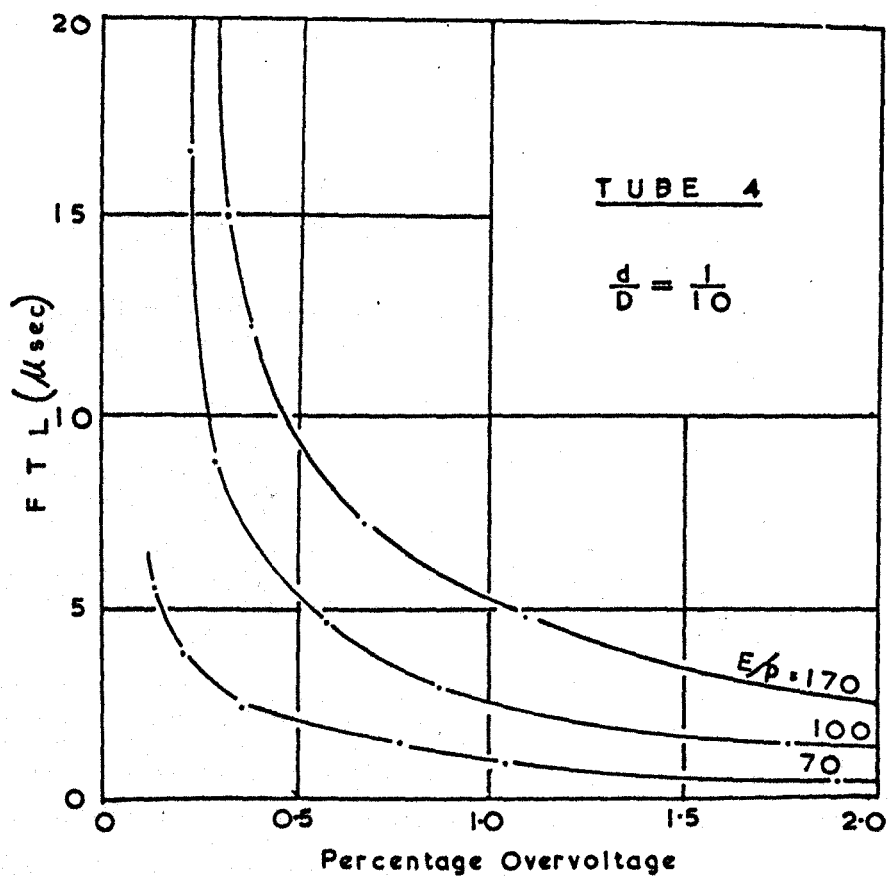
FTL vs. Percentage Overvoltage

Fig 32



FTL vs. Percentage Overvoltage

Fig 31



FTL vs. Percentage Overvoltage

Fig 30

considered points, and t_1 and t_2 are the FTL's at those points. This procedure was adopted for all the curves obtained from tube 4 of FTL's vs. $(V_B + V_p)$, and the corresponding FTL vs. percentage overvoltage curve obtained. These curves were then grouped together for the various gap geometries (i.e. d/D ratios) considered, and are shown in figs 30 to 32.

The curves shown in figs 30 to 32 have the usual shape, and the magnitudes of the FTL's are comparable with those found with the earlier tubes, though the lower pulse voltage did enable longer time lags to be observed than with tube 2, the earlier tube with gold electrodes. An examination of the curves for the three considered gap geometries, shows that for a given d/D , an increase in the displacement of the experimental curves from the origin was associated with an increase in E/p . This has always been found, and is interpreted in terms of a decrease in the ratio of the photon secondary coefficient to the generalized secondary coefficient (i.e. a decrease in $\frac{\delta}{\alpha} / \frac{W}{\alpha} = \frac{\delta}{W}$) as E/p increases. Further, as was observed with tube 2, the FTL increases linearly (to within 5%) with E/p for a given overvoltage.

Attempts were made to interpret the results with the aid of Davidson's theoretical expressions. Since a range of E/p was being considered, it would have been a formidable task to have constructed a set of curves, such as those presented in section 5.6 for all the different E/p 's.

Instead, particular curves were selected, and an estimate made of the importance of the two possible secondary processes. The mathematical expressions used were Davidson's approximate ones, the method employed having been briefly considered in section 4.5. These expressions are valid for FTL's which are greater than a few electron transit

times; in this experiment the longest transit time of an electron would have been less than 10^{-7} sec, more than an order of magnitude smaller than any measured FTL's, and hence the approximate expressions are quite adequate for this investigation. They cannot, however, be expected to yield a precise value for the FTL, since they assume that prior to the gap being overvolted there is no voltage across the gap, and no U.V. illumination of the cathode. In this experiment a backing voltage, V_B (V_B less than V_g) was always applied across the gap, and the cathode was always illuminated with U.V. light. Hence there were always pre-breakdown currents flowing across the gap which would have had the effect of reducing the FTL. It was reported in section 5.2, however, that changing V_p from 100 V to 10 V produced no appreciable change in the FTL, and hence the effect of the pre-breakdown currents was quite small.

Values of α , w/α , w_+ and w_- have to be inserted into Davidson's expressions. α was taken from Fletcher's results (61) w/α obtained from Townsend's breakdown criterion, w_- extrapolated from lower E/p values (see section 6.2), w_+ was also at first taken as 10^{+2} times w_- . The uncertainty of the w_- and the w_+ values introduced grave uncertainties concerning the magnitudes of the individual secondary coefficients, δ/α and γ .

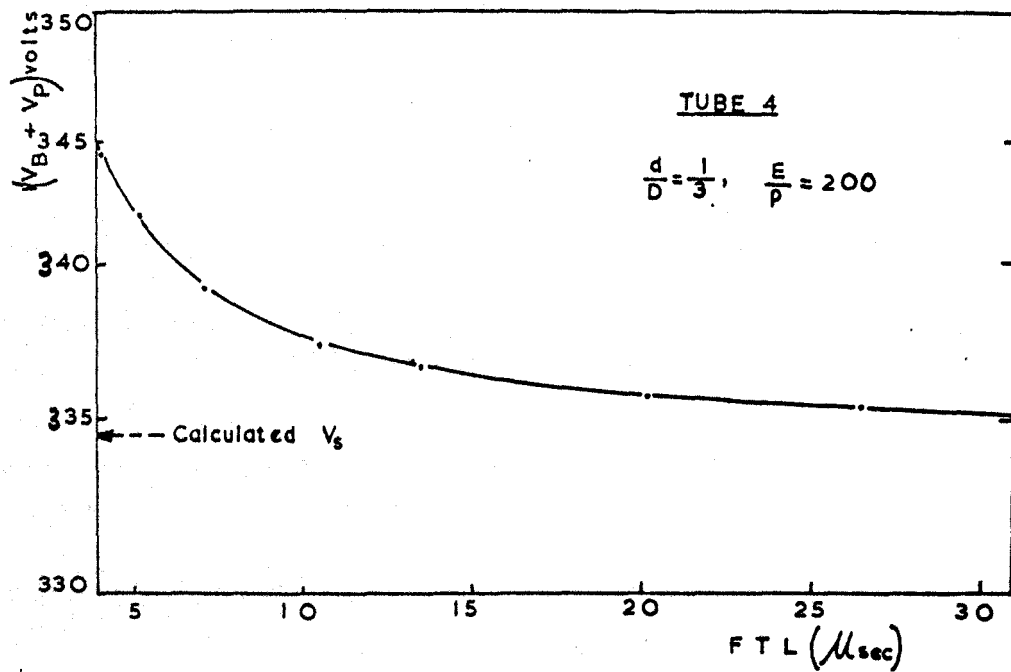
The curves obtained for the low E/p values (about $70 \text{ V}(\text{cm.mma Hg})^{-1}$) were first considered. The calculated curves obtained for the same E/p assuming that the photon process was the sole secondary process, produced FTL's which were less than the measured values, and it appears that the positive ion process must be active, though the analysis suggests that 90% of the secondary action was photon action at the cathode. This is a little higher than has been reported by other workers (50), though since low

values of E/p were being considered, and it is in that region that E/p varies rapidly with p and d , it is apparent that small errors in measuring the gap distance or gas pressure could have produced a substantial variation in the primary ionization coefficient, α . A further factor, also, could be the fact that other workers were using different α values. Fletcher found that his α/p curve lay lower than other determinations, and the lower α value thus indicated in the gap could perhaps account for the higher magnitude of the ion coefficient, γ . For these reasons then the small discrepancy with other workers at low E/p 's might well not be at all significant.

The analysis was repeated for E/p 's of 100 and $200 \text{ V}(\text{cm.mm Hg})^{-1}$ for both a d/D of $1/10$ and $1/3$, with the same result, that the photon secondary process was responsible for 90% of the total secondary action. This is quite different from the results of the work at Swansea (50,53) and in this laboratory (51). They had all previously reported that at an E/p of $200 \text{ V}(\text{cm.mm Hg})^{-1}$, photon action was only responsible for 60% of the secondary action. If this was so in this experiment, the FTL at 2% overvoltage with a d/D of $1/3$ would have been $100 \mu\text{sec}$, a value very much greater than that measured at any time during this investigation. There are, however, a number of factors which could contribute to the discrepancy between these results and those found in other investigations. These will now be briefly considered.

The sparking potential is an extremely important parameter, and a small error in that could change the FTL vs. percentage overvoltage curves substantially. Morgan and Gozna both defined their sparking potential as being the smallest voltages which produced a self-maintained discharge. Morgan then applied his voltage from an impulse

generator (no backing voltage was used) while Gozna used the same arrangement as in this experiment, the total voltage being the sum of a backing voltage (V_B) and a pulse voltage (V_P). It is questionable whether Morgan's definition of the sparking potential was the best that he could have chosen, but certainly that employed by Gozna could introduce substantial errors into his overvoltage determinations. Gozna applied say 1% overvoltage, by making $(V_B + V_P)$ equal to $(101/100)V_S$, where V_S was the sparking potential, measured by using only his bank of batteries, no pulse voltages being employed. He makes no mention of how V_P was measured, but states that a 100 V pulse was used, presumably the pulse voltage, V_P , was measured using the Tektronix 545 oscilloscope. When measured on the 545A oscilloscope the "100 V" pulse from the same pulse generator, was actually nearer 105 V, but such readings cannot have an error less than 5% associated with them. Such a 5% error in the pulse voltage readings would have produced a similar error in the applied voltage readings and overvoltage values, when backing voltages of the order of only 200 V were used. For these reasons, Gozna's curves showing the individual secondary coefficients as functions of E/p can only be regarded as being preliminary results. The method employed in this investigation to evaluate the sparking potential, does seem to be better than Morgan's and Gozna's, since it is directly related to the actual breakdown measurements. Ideally, of course, their method and the method employed here should produce the same result; this was not tested in this investigation except at the conclusion of the experiment, when the experimental tubes had quite a high gas pressure inside them (high p implies low E/p), and the agreement then was within about 2%. This need not be so at lower



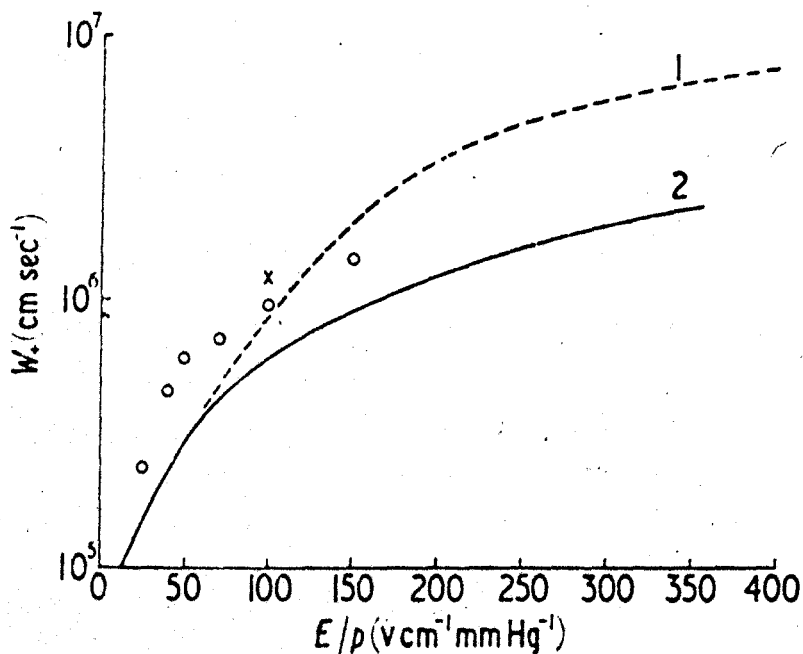
Semi-logarithmic Plot of FTL vs. $(V_B + V_P)$.

Fig 33

pressures (and thus higher E/p 's) though. The method used here, however, is far more convenient in that only a single set of FTL vs. applied voltage readings are required, the overvoltages then being easily evaluated. Fig 33 shows a curve of the FTL vs. $(V_D + V_P)$ on semi-logarithmic paper, and it can be seen that the increase in FTL at the higher end of the FTL curve is virtually exponential, and it is seen to be quite impossible for the V_g evaluation to be so much at fault, as would be required for a 100 μsec FTL to be obtained at 2% overvoltage.

Having considered the evaluation of the sparking potential, some aspects of the mathematical analysis will now be considered. The mathematical expressions themselves are only approximate, but are expected to produce quite good estimates of the FTL under the experimental conditions. Various constants, however, have to be used in the equations, constants moreover which have not yet been adequately measured. Values of α are Fletcher's values (61), and are considered to be the best available. Values for w/α , and hence the sum of δ/α and γ , are calculated using Townsend's breakdown criterion, and hence are the relevant values for this experiment. Difficulty arises when the values for positive ion and electron drift velocities in hydrogen are considered (w_+ and w_-).

The electron drift velocity in hydrogen, w_- , has not been measured for a range of E/p greater than about $40 \text{ V}(\text{cm.mm Hg})^{-1}$, and hence the values for w_- at the higher E/p 's have to be extrapolated from these lower E/p values. The positive ion drift velocity, w_+ , also has not been measured for a large range of E/p , and at first its value was taken as being 10^{+2} times w_- . The uncertainties in these drift velocity values make the conclusions drawn from the analysis very tentative. Jones and Llewellyn



Drift velocity W_+ plotted against E/p . Curve 1, new estimate of probable values of W_+ ; curve 2, linear extrapolation of Bradbury's (1932) measurements giving a mobility of 8.2 at $E/p < 50$; o, Rose's (1960) measurements at low current densities; x, Rose's (1960) measurement at high current density.

Fig 34

Jones (63) have recently questioned the values for the positive ion drift velocity which they had used earlier (53), and have published an account of a theoretical analysis which was conducted in order to ascertain the value which the photon coefficient, δ/α , could have in the range $50 < E/p < 250 \text{ V(cm.mm Hg)}^{-1}$, and they found that the maximum value for δ/α was, at higher E/p 's much less than that estimated in their earlier paper (53) when they analysed their FTL curves. They concluded that the only feasible reason for this was an error in w_+ , and they have found that at an E/p of say $200 \text{ V(cm.mm Hg)}^{-1}$, w_+ would have to be increased by a factor of about three, in order that the values for the photon coefficient was reduced sufficiently for it to agree with the value obtained from theoretical considerations. They have accordingly drawn a graph of their newly postulated values for w_+ which is shown in fig 34, together with the values of w_+ obtained from the earlier extrapolation. When Jones and Llewellyn Jones used these new positive ion drift velocities they found that the photon coefficient remained at about a constant value of just over 10^{-3} over the whole range of E/p encountered in this experiment (up to $200 \text{ V(cm.mm Hg)}^{-1}$), while the positive ion coefficient was almost negligibly small up to an E/p of $100 \text{ V(cm.mm Hg)}^{-1}$, at which point it increased rapidly until at an E/p of $200 \text{ V(cm. mm Hg)}^{-1}$ it was at a maximum of 0.05. Hence they now maintain that positive ion action is the predominant secondary process at these high E/p 's, but until the drift velocities of the positive ions and electrons have been determined experimentally, doubts must exist as to the values of the secondary coefficients. If the new positive ion drift velocity extrapolation is used for the results of this experiment, the positive ion secondary process becomes

responsible for some 40% of the secondary action, at an E/p of $200 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$. The Swansea workers estimated more than 90% at the same E/p .

5.9 Conclusions from the low overvoltage breakdown experiments and suggestions for further work in this field.

In this work a study has been made of the secondary ionization coefficients, active in low pressure hydrogen discharges under small overvoltages. At low E/p (say $70 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$), the photon process was seen to be the predominant secondary process, accounting for up to 90% of the secondary action. As E/p increased, the contribution of the positive ion process increased, until at an E/p of $200 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$, it accounted for some 40% of the secondary action (calculated by assuming Jones's revised positive ion drift velocity curve). Other workers have found that the positive ion's contribution was higher than that found in this investigation. The discrepancy could well be a result of the different methods used in evaluating the sparking potential. The method used in this investigation does seem to be the easiest to use in practice, and is more directly relevant to actual FTL measurements. The actual figures obtained for the relative importance of the secondary coefficients must still, however, be regarded tentatively, as the analysis upon which the breakdown theory is based, requires the values of w_+ and w_- , these parameters have not been measured for the whole range of E/p considered in this investigation.

It would be interesting in some future investigation to establish whether the different methods of evaluating the sparking potential do in fact produce identical values for V_g over the whole range of E/p , and further to establish

the effect of varying the geometry of the gap. It was considered that these results indicated that the photon process would very probably be decreased in magnitude, as the gap distance was increased at a constant E/p , though no quantitative estimate of its importance could be made without comparing the results of a series of tubes having different electrode diameters.

CHAPTER VI

RESULTS AND DISCUSSION OF THE HIGH OVERVOLTAGE BREAKDOWN EXPERIMENTS.

6.1 Introduction.

In this chapter, the work which was conducted at the higher overvoltages is described. Dawson initiated the higher overvoltage experiments in this laboratory, and the work described here is a continuation of his work, which was considered briefly in section 2.4. The breakdown of highly overvolted gaps, presents quite different experimental problems to those found at the lower overvoltages. discussed in the last chapter, and further the physical processes involved may also be different. In the following section, the nature of the high overvoltage problem is considered, and in sections 6.3 and 6.4 the actual results obtained are presented.

6.2 Breakdown under high overvoltages in hydrogen.

The Townsend breakdown criterion at the sparking potential, V_s , is

$$\frac{w}{\alpha} (e^{ad} - 1) = 1$$

At voltages less than V_s , $\frac{w}{\alpha} (e^{ad} - 1)$ will be less than unity, and at voltages greater than V_s , it will be greater than unity. For instances where $w/\alpha = 10^{-6}$, the multiplication of a single avalanche, e^{ad} , is of the order of 10^6 , a multiplication high enough to be observed on an oscilloscope. With hydrogen, however, at the sparking potential, w/α is of the order of 10^{-3} and hence e^{ad} is of the order 10^3 , a value too small for the avalanche growth to be detected. At very much higher overvoltages, it should be

possible to increase this multiplication to a value which would allow the growth of a single avalanche to be detectable with an oscilloscope.

Under the conditions encountered in the low over-voltage breakdown experiments, reported in chapter 5, three ionization processes could have been active. The primary, α , process was the only process active in the gas, while the photon secondary process, δ/α , and the positive ion process, γ , could have been active at the cathode. At higher overvoltages, FTL's can be observed which are so short that the positive ion process could not have been active, and sometimes the photon process could not have been active either. Under these conditions, breakdown can involve a primary process alone. It should be noted, however, that gas photo-ionization could also be possible at very high overvoltages, there being much evidence to show that when it is active, the breakdown process can be very much faster, and quite different from the Townsend model. This faster process, known usually as the streamer process was considered briefly in section 2.3 and though being generally accepted, has not been universally accepted. Workers at Swansea still refuse to accept the validity of the theory and are still attempting to interpret their experimental results, under conditions where space charges become important, by postulating amended values for the secondary coefficients, δ/α and γ (63).

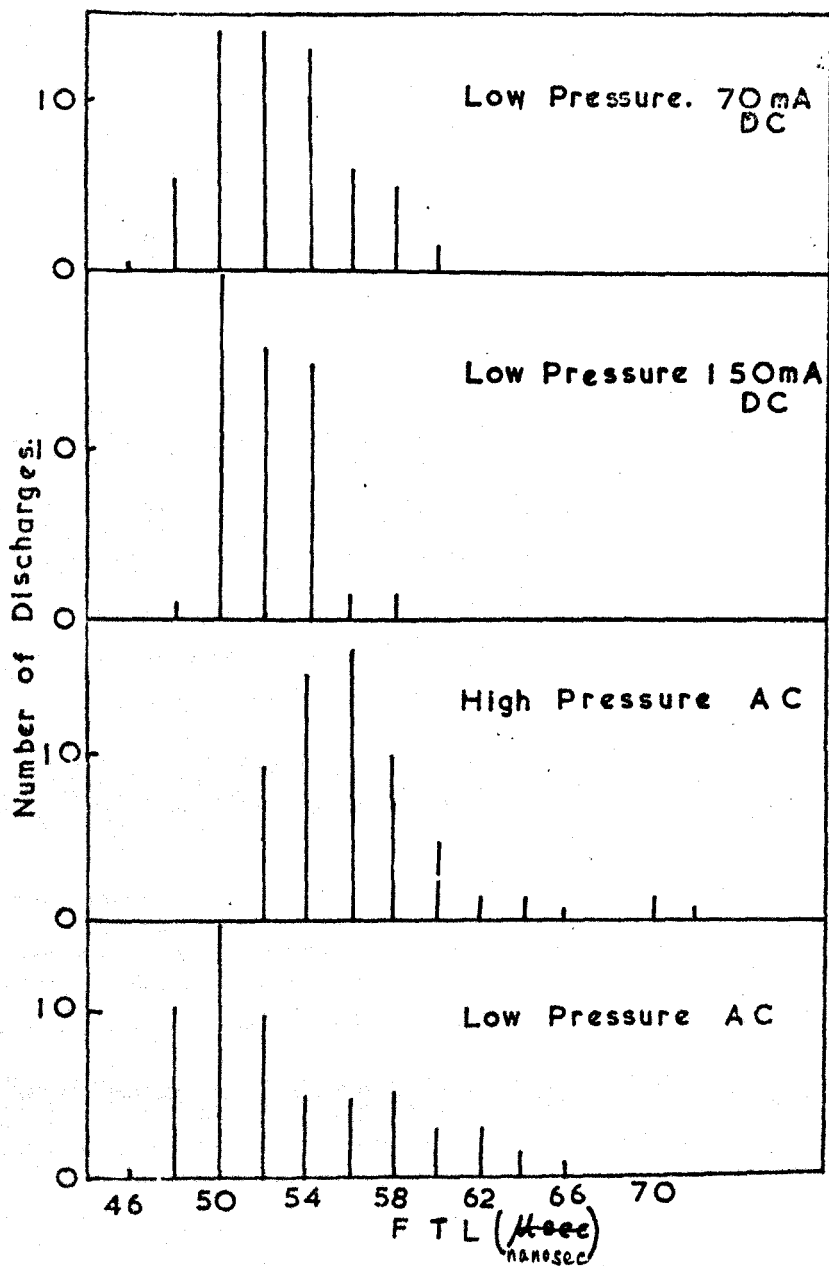
If the FTL was so short that breakdown could have been a primary process alone, then a value for the "apparent drift velocity" of the electrons can be calculated from the equation

$$I = \frac{qW_-}{d} e^{aW_-t}$$

Where I is the smallest current which can be observed on the oscilloscope, $8 \cdot 10^{-3} \text{A}$, q is the electronic charge, d is the gap distance, t is the FTL, w_- is the drift velocity of the electrons and α is the primary ionization coefficient. For a current of $8 \cdot 10^{-3} \text{A}$ to be created in a single avalanche, the multiplication, e^{ad} , has to be at least equal to 10^8 , and hence if e^{ad} is greater than or equal to 10^8 , the gap would be expected to break down in a time less than or equal to the electron transit time (assuming values of α are unaffected by the avalanche growth). The electron drift velocity, w_- , has not been measured in hydrogen for all the E/p range encountered in this experiment. In order to obtain an estimate of its value, the curve obtained for the very low E/p region has to be extrapolated to higher E/p values. Dawson adopted the extrapolation, $w_- = 6 \cdot 2 \cdot 10^6 (\frac{E}{p} - 40)^{1/2}$, and this will be used in this investigation also. The "apparent drift velocity" of the electrons crossing the gap can, of course, be modified by a number of factors. At the high over-voltages considered, the multiplication of a single avalanche will be so high, that space charge fields will develop which could appreciably alter the drift velocity. The variation of "apparent drift velocity" with E/p found with tube 6 will be considered in section 6.4, while in section 6.3 the results of some preliminary tests will be described.

6.3 Preliminary tests.

Before any results were taken to investigate the active breakdown process, a short investigation was conducted to establish the importance of some of the experimental features which could be altered.



Histograms Obtained From Tube 6

Fig 35

U.V. sources.

Two types of mercury U.V. lamps were available in this laboratory, one operating at high pressures and the other at low pressures. Both were usually run from an A.C. supply. Dawson used a low pressure lamp which he ran from the usual A.C. supply, but there did seem to be the very real possibility that the nature of the light output from the A.C. discharge could influence the FTL. Both lamps were used in these tests, and efforts made to run them from a D.C. supply, in an attempt to establish whether any variation in the FTL could be obtained. The low pressure lamp required a current of some 100 mA to function adequately, while the high pressure lamp required a current of several amps. It was actually quite a straight-forward matter to run the low pressure lamp from a D.C. supply. The voltage source was a stabilised power-pack, and with a suitable resistor in the circuit a current of about 150 mA, at a voltage of 150 V was passed through the lamp. The circuit resistor consumed a lot of power, and it was found convenient to use an electric light bulb as that resistor. In order to examine the FTL's accurately, the traces were photographed. Visual observation was of little use, owing to the very short persistence time of the screen.

The FTL's obtained from tube 6 using the different U.V. lamps were first examined. The high pressure lamp could only be used from the A.C. supply, but the low pressure lamp was run from both an A.C. supply and a D.C. supply; in the latter case, currents of 70 mA and 150 mA were drawn. 60 breakdowns were recorded for each lamp, and the results, shown in fig 35, obtained. The low pressure lamp, when drawing the higher D.C. current can be seen to produce the least spread in FTL's. It is very

probable that this is a result of the increase in intensity of the light output, obtained by running the lamp on 150 mA from the D.C. supply. Thomas, in this laboratory, used a similar lamp in order to produce the initial photoelectric current across her experimental gap, and she found that the current I_0 , was doubled on changing from the A.C. supply to a 150 mA, D.C. supply. All the subsequent results reported in this chapter are taken with the low pressure lamp run from a D.C. supply taking a current of 150 mA. The results obtained from the low pressure lamp when only a 70 mA current was being drawn from the D.C. supply, and when the A.C. supply was being used, show the same FTL as occurring most frequently, but there is a much wider spread in the FTL's, presumably due to the decreased intensity of the light output. The results obtained from the higher pressure lamp are somewhat different from those obtained with the low pressure lamp; the spread in FTL's is very high, and the FTL which occurs most frequently is about 4 nsec higher than for the other lamp. The light spectra from the two lamps are, of course, a little different. 99% of the emission from the low pressure lamp is in the 2536 Å line, while the emission from the high pressure lamp is spread over a wider range, and it could well be that the intensity of the radiation in the high pressure lamp, capable of producing photo-electrons was less than in the low pressure lamp. The low pressure lamp functioned quite adequately and hence it was decided to use it for all the subsequent readings. It should be noted also, that these histograms were obtained quite early in the investigation, at which time the electrodes had had only a preliminary cleaning treatment. After the electrodes had been cleaned again, using the eddy current heater, the spread in the FTL's was further reduced.

Effect of I_0 .

The effect of reducing I_0 by increasing the distance between the lamp and cathode was also considered. The smallest lamp-cathode distance obtainable was 11.5 cm (and was used when obtaining the results shown in fig 35), and using such a value, it was quite a simple matter to decide which was the most frequently occurring FTL. On increasing the lamp-cathode distance to 18.5 cm, while using the low pressure lamp with a current of 150 mA, the same FTL was seen to occur most frequently, but the distribution of FTL's was very much wider and the peak much less pronounced. On increasing the lamp-cathode distance to 24 cm it was no longer possible to determine a FTL which occurred most frequently, the FTL's being distributed over some 20 nsec. To have taken the mean of these as being the FTL would have produced a value some 10 nsec greater than the FTL which occurred most frequently for the smallest lamp-cathode distance.

Effect of different repetition periods.

Different repetition periods were used, ranging from 2.5 sec to 20 sec. No appreciable difference was found in the distribution of FTL's over the whole of this range. A repetition period of about 5 sec was used for all the results quoted later.

Summary of the preliminary tests.

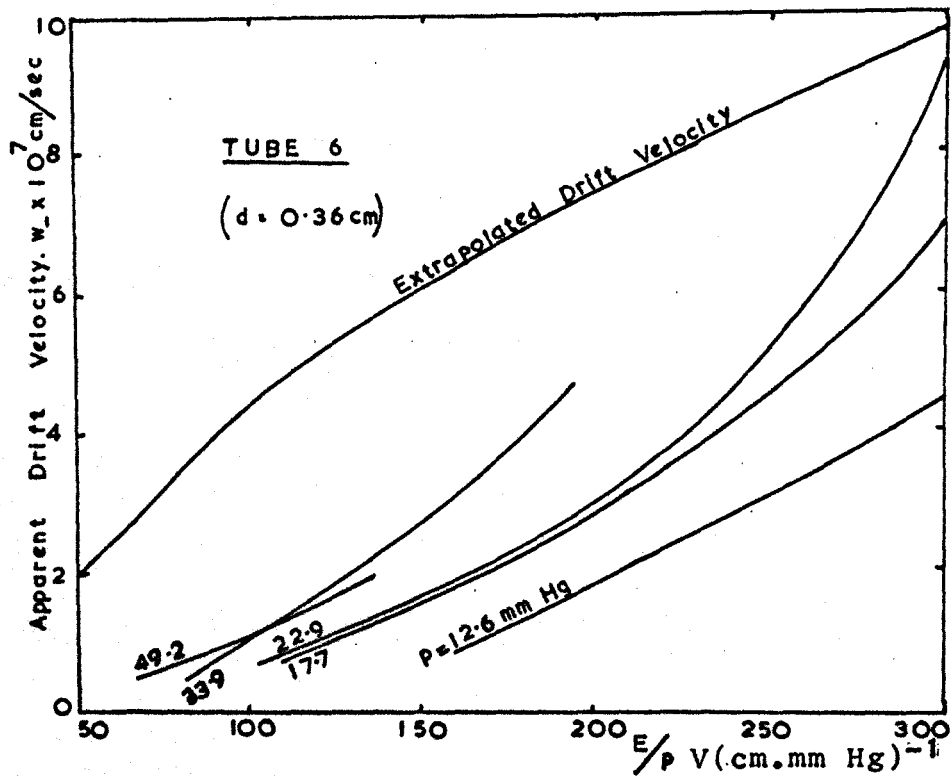
For the low pressure lamp, and lamp-cathode distances which could be considered in these tests, intensities could be obtained which were sufficiently high to reduce undesirable statistical fluctuations in the FTL's to an acceptable level. The most frequently occurring FTL (where such a value could be determined), did not change as the light intensity from the low pressure lamp was changed.

The low pressure lamp as used in this experiment would produce an initial photo-electric current of the order of 10^{-11} A, this proving to be quite adequate to enable the FTL to be obtained satisfactorily.

In this section the tests carried out to determine the best way of illuminating the cathode and of applying the voltages to the gap have been described, and the practice considered to be best outlined. In the following section the results obtained in the major part of the investigation are presented and discussed.

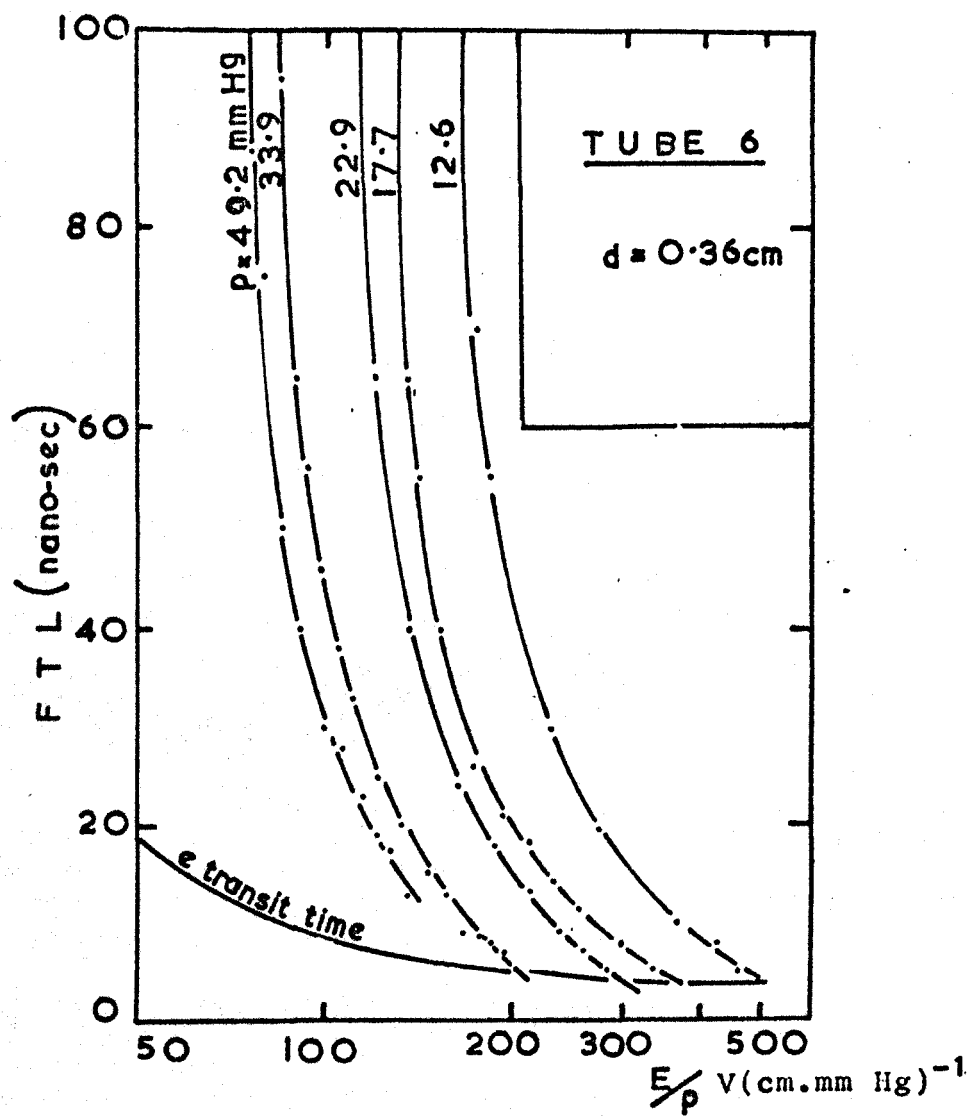
6.4 Results and discussion of the results from tube 6.

It was convenient in this experiment to measure FTL's for a range of E/p's at constant gas pressure (and, of course, gap distance). It was explained in section 2.4 that the concept of a sparking potential, and a precise overvoltage, are not really meaningful under the conditions of this experiment, and hence the experimental results are first presented in the form of a FTL vs. E/p curve. The actual E/p applicable for any particular charging voltage, has first to be determined. The pulse is attenuated on travelling along the cables to the experimental tube, by an amount which can be estimated by examining the actual voltage pulse on the oscilloscope. The experimental tube is shorted out, the pulse being fed across the auxiliary spark gap, through the 825 ohm resistor and into the oscilloscope. The sensitivity of the oscilloscope is 10 V per cm, hence to examine higher voltage pulses, attenuators were required. The attenuation for the pulses passing through the cables to the experimental tube was found to be 17%, and in fact increased slightly as the voltage pulse amplitude was increased. All the FTL's were measured visually, it being



Apparent Drift Velocity vs. E/p

Fig 37



FTL vs. E/p

Fig 36

easily seen which was the most frequently occurring value, and this time being defined as the FTL for those particular conditions. Fig 36 shows the results obtained with tube 6, the different curves being obtained at different pressures. From these curves it can be seen that at a given pressure, the FTL always decreases as E/p increases, and that at any given E/p , the FTL decreases as the pressure increases. Fig 37 shows the results of the calculations to find the apparent drift velocity of the electrons, assuming that all the breakdowns considered in fig 36 were, in fact, single avalanche breakdowns.

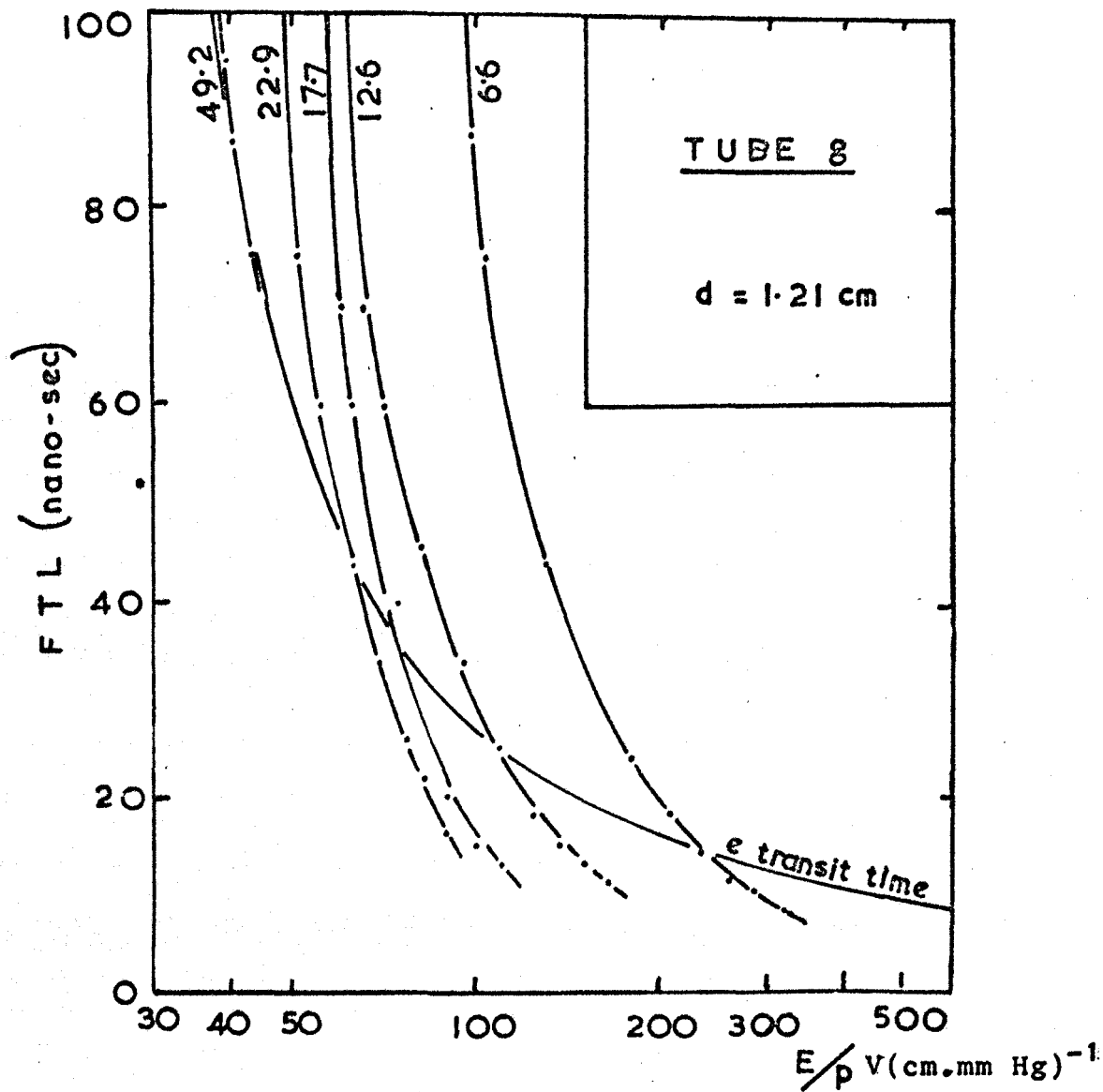
It is apparent from these two figures that some process is active which tends to retard the avalanche growth as it crosses the gap. Some of the points shown on fig 37 relate to points where e^{ad} is higher than 10^8 and yet breakdown takes longer than the expected electron transit time. Such behaviour suggests that high positive ion space charge fields develop near the anode which are high enough to slow down the motion of the electrons at the rear of the electron swarm, thus effectively reducing the value of the primary ionization coefficient, α . This thus causes the electron cloud to become distended and causes the average drift velocity of the electrons to the anode to be reduced. It becomes apparent that the multiplication, e^{ad} , obtained by using Fletcher's α values will give quite erroneous values for the actual multiplication.

Having seen that space charges are created in the gap which tend to retard the avalanche growth, the variation of the FTL with E/p for a given pressure can now be understood. As E/p increases, α/p increases, and hence the theoretical multiplication in an avalanche as it crosses the gap also increases ($ad = p.d \cdot \alpha/p$). Thus even though

α is reduced by the space charge effects, the increase in the theoretical multiplication implies that the actual multiplication of the initial avalanche will be increased, and hence its contribution to the production of the breakdown current will be enhanced. Secondary processes thus decline in importance as E/p , and hence the initial gas multiplication, increases. It should be noted also, however, that while the contribution from the secondary effects might be expected to decrease in significance for the higher E/p 's, the actual magnitude of the photon cathode coefficient will in fact be increased slightly at the higher E/p 's. This would tend to reduce the FTL's at the higher E/p 's, though its effect may not be at all significant, since as the FTL is decreased, the number of photons which could produce secondary electrons from the cathode will be reduced.

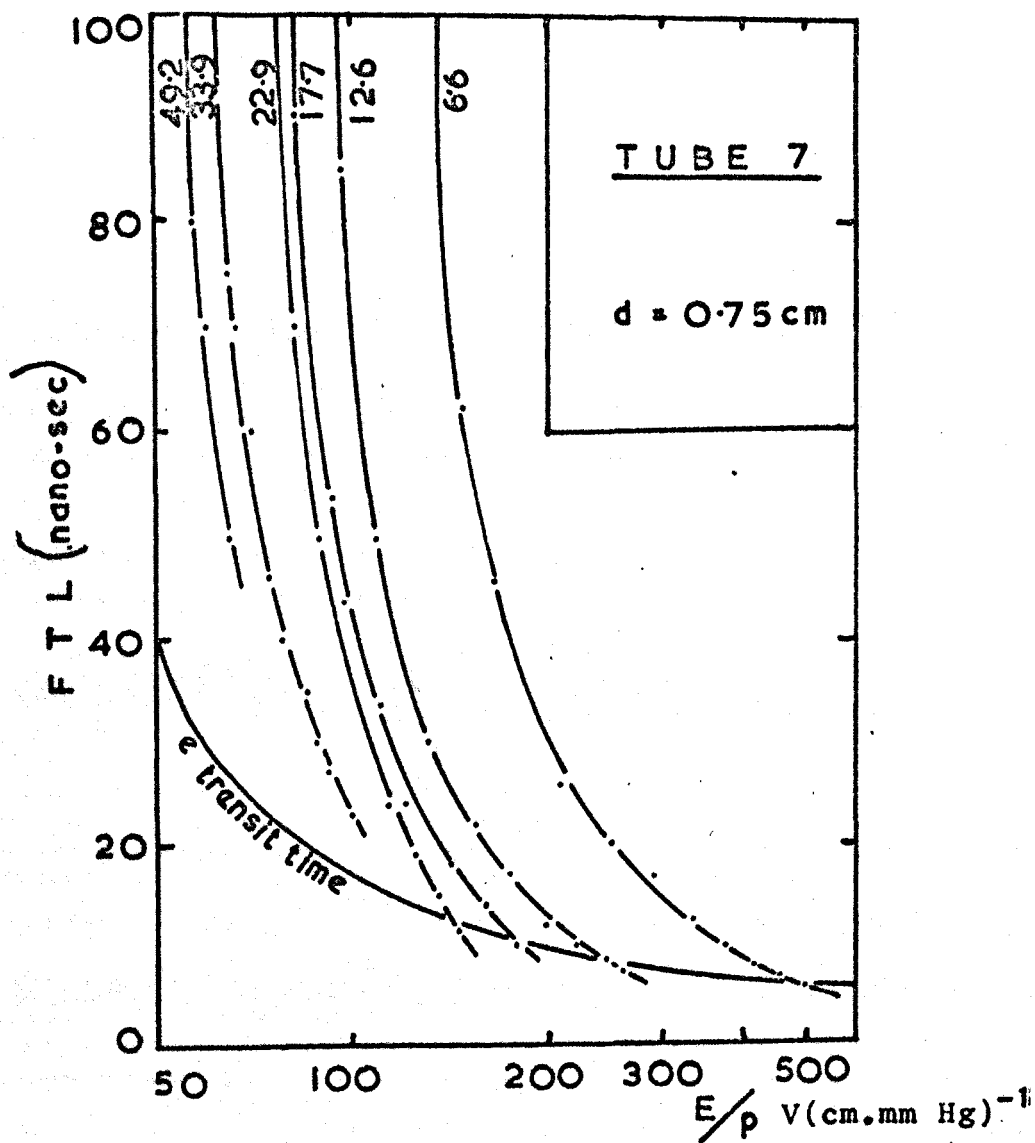
The variation in FTL with pressure, for a given E/p can also be understood in terms of the multiplication of the initial avalanche. For a given E/p , α/p will of course be constant, and hence the gas multiplication e^{ad} will increase as the pressure increases ($ad = pd \cdot \alpha/p$). Again this implies that the FTL will be determined more by the growth of the initial avalanche, the contribution from the secondary processes decreasing as the pressure increases. In addition to this factor, the reduced diffusion of the electron swarm at the higher pressures could also result in the multiplication of the initial avalanche being enhanced.

The results obtained from tube 6 can thus be explained qualitatively. It must also be remembered that the FTL's obtained at the high E/p end of all the experimental curves are comparable with the voltage pulse rise time and hence are somewhat unreliable; too much



FTL vs. E/p

Fig 39



FTL vs. E/p

Fig 38

consideration should not therefore be given to these FTL's. Dawson obtained similar results to those shown for tube 6, though when plotting the apparent drift velocities, he found that his apparent drift velocities were sometimes very much greater than the extrapolated drift velocity curve. This was not found in this investigation with tube 6, though there are several possible factors which could result in such a difference. The calculation of the actual voltage pulse height is dependent on the measuring of the attenuation factor for the pulse as it passes along the cables. This cannot be determined with an error less than 5%, and slight fluctuations in the pulse amplitude of at least 5% along the length of the pulse, imply that that E/p stated as abscissae has a substantial error associated with it. Further, the rise time of the pulse (5 nsec in this experiment, but only 2 nsec in Dawson's) is of the same order as some of the FTL's measured in this experiment.

Thus the discrepancies between these results and Dawson's, could well be accounted for by the errors associated in the experiments themselves. Because of the errors associated with the results and the difficulty of obtaining a quantitative estimate of the space charge effects, it is not possible with the experimental arrangements used, to obtain more than the qualitative effects of varying the pressure and E/p . It was considered that some further information could be obtained by varying the gap distance, and thus two further tubes, numbers 7 and 8, were constructed having gap distances of 0.75 cm and 1.21 cm. The results from these tubes are presented in the following section.

6.5 Results and discussion of the results from tubes 7 and 8.

Figs 38 and 39 show the curves of FTL vs. E/p for

tubes 7 and 8, where it can be seen that the curves have a very similar shape to those from tube 6, though of course are displaced to lower E/p values. The same effects on the FTL of pressure at a constant E/p, and of E/p at a constant pressure can be observed, and presumably are again a feature of the increased initial avalanche multiplication as either the pressure increases for a given E/p, or E/p increases for a given pressure.

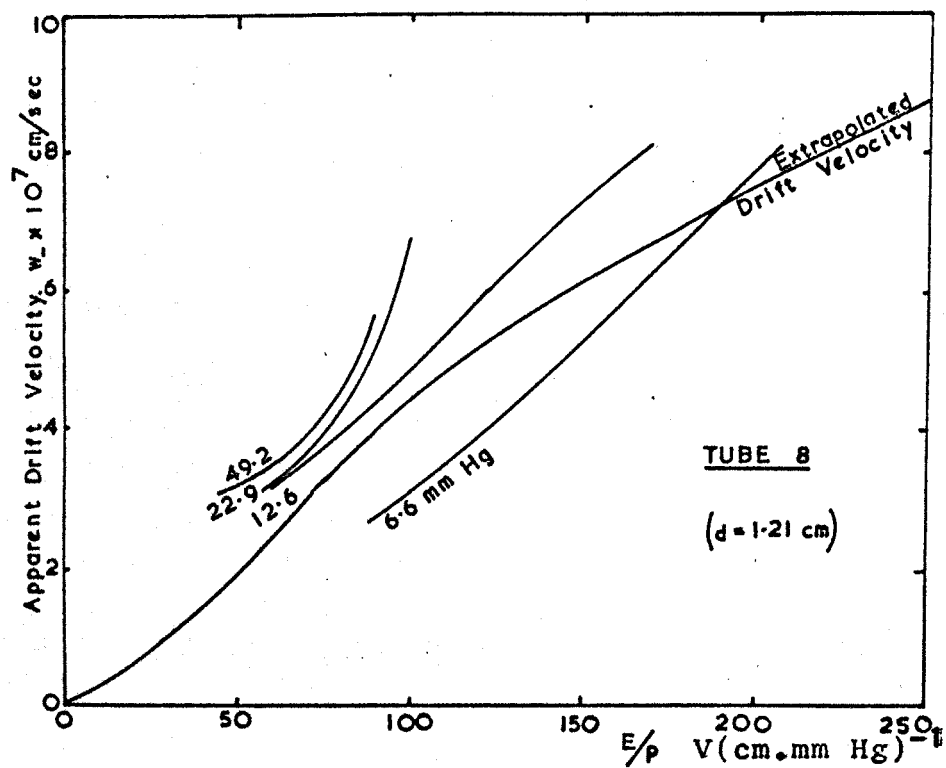
It is interesting to consider the expected electron transit times, shown on figs 36, 38 and 39, which have been calculated using extrapolated drift velocity values. The transit time curve can only be regarded tentatively at this stage. For breakdowns with FTL's less than transit times on figs 36, 38 and 39, the avalanche multiplication is adequate to produce breakdown in the absence of space charge, and further, if the FTL is less than 10 nsec, then the contribution of any secondary processes can only be very small. It is possible to compare two FTL's at an E/p of $180 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$ with tubes 6 and 7. Consider the 33.9 mm Hg curve with tube 6 and the 17.7 mm Hg curve with tube 7. The product of pressure and distance for both tubes is very nearly the same, and if it is assumed that such breakdowns are single avalanche breakdowns, then the ratio of the expected FTL's can be calculated from the equation:

$$I = \frac{q w_-}{d} e^{a w_- t}$$

as

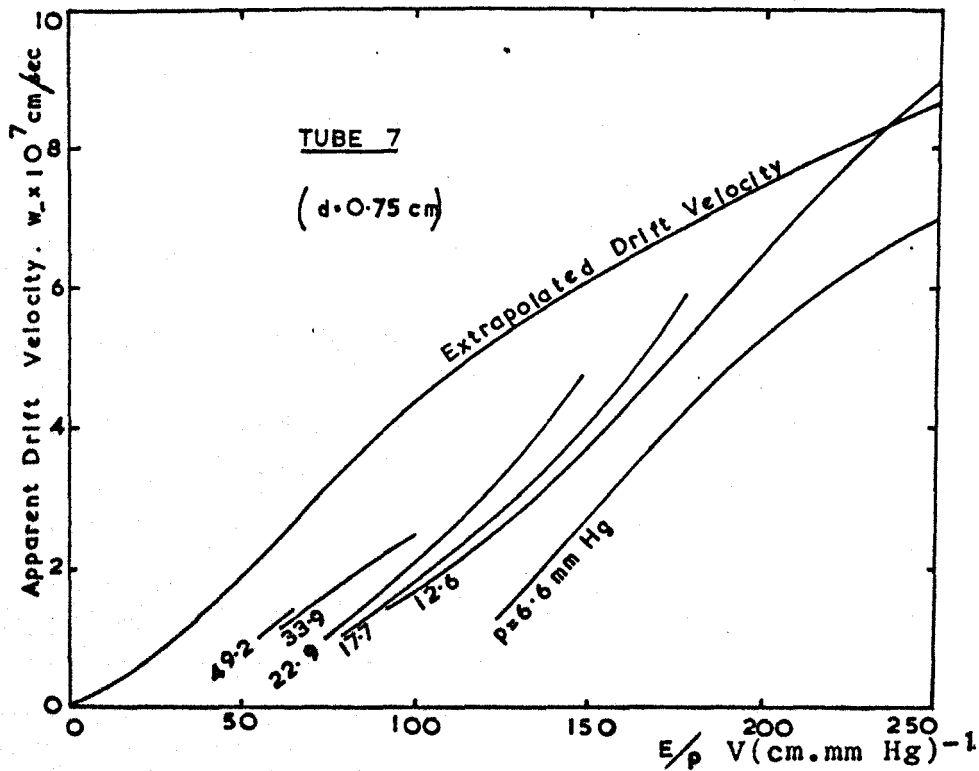
$$\frac{\text{FTL}(\text{tube 6})}{\text{FTL}(\text{tube 7})} = \frac{17.7 \ln\{0.36 \cdot I/qw_-\}}{33.9 \ln\{0.75 \cdot I/qw_-\}} \sim 1/2$$

where I is the current taken to indicate breakdown, q is



Apparent Drift Velocity vs. E/p

Fig 41



Apparent Drift Velocity vs. E/p

Fig 40

the electronic charge and $w_$ is the electron drift velocity. In fact the FTL obtained with tube 6 is $3/4$ of that obtained with tube 7, which is an indication that the breakdown might well be a single avalanche breakdown. The value of ad is 24.4 in tube 6 and 26.6 in tube 7 which are somewhat greater than the value of 20 which would be expected to be sufficient to indicate breakdown in the absence of space charge, though it is hardly surprising that the theoretical ad is greater than 20, since it is to be expected that the value of α in the tubes will be less than Fletcher's values because of the space charge effects.

If the curves for tubes 6, 7 and 8 are compared, it can be seen that for a given E/p and pressure, the FTL decreases as the gap distance increases. This behaviour can be explained qualitatively in that in the higher gap distances, the initial avalanche multiplication will be increased, and hence the contribution of the secondary avalanches will become increasingly less significant as the gap distance increases, the FTL becoming more predominantly equal to the growth time of the initial avalanche. This behaviour is perhaps made clearer when the apparent drift velocity curves for tubes 6 and 7 (calculated from the FTL curves) are examined. The apparent drift velocity increases with gap distance for a given E/p and pressure, implying that at larger gap distances the breakdown is tending towards single avalanche breakdown. The larger gap distances will also have the effect of reducing the charge density in the gap at any particular point, thus the reduction in α values will also be expected to be smaller.

The apparent drift velocity curve for tube 8 is at first confusing, in that for the higher pressures the apparent drift velocities all lie above the extrapolated

values, even though the FTL's are sometimes longer than the expected transit times. The reason for this is that the expected electron transit time is calculated from the extrapolated drift velocity curve, while the apparent drift velocity curve is calculated from the FTL curves, and these two sets of curves are quite distinct. The first pair mentioned are merely postulated quantities extrapolated from other experimental data, while the latter pair are calculated from the experimental points, assuming that breakdown is by a single avalanche (which it sometimes quite definitely is not). If we then consider an actual point on the experimental FTL curve, say at an E/p of $55 \text{ V}(\text{cm.mm Hg})^{-1}$ and a pressure of 22.9 mm Hg, where the FTL is 60 nsec, some 7 nsec longer than the expected electron transit (calculated from extrapolated drift velocity values), the apparent drift velocity is calculated by assuming that the breakdown is by a single avalanche and finding the value of w_0 in the equation above which in fact will produce the breakdown current of 8.10^{-3} A . Such a value of apparent drift velocity is found to be greater than the extrapolated drift velocity. This calculation, however, takes no account of the variation in α , and takes no account of the contribution of secondary electrons. Thus $(\alpha w_0 t)$ has to reach a certain value to produce breakdown, and in this case when the FTL ($=t$) is only about 13% greater than the electron transit time, the value of w_0 has also to be increased for the single transit model. Physically this is absurd, since for a longer crossing time the drift velocity must of course decrease, this absurd result being a feature of the incorrect model employed. This is not observed at the smaller gap distances, where the FTL is usually many times the electron crossing time, and sometimes more than an

order of magnitude greater than the expected electron crossing time. In these smaller gap width breakdowns, the value of the FTL is so large that the w_0 in the equation is usually found to be smaller than the extrapolated drift velocity values. Thus the results of the calculations for smaller gap widths, fit in with the physical model, while at the larger gap widths, the inadequacies of the model become apparent and absurd results ensue.

6.6 Conclusions to be drawn from the high overvoltage experiments and suggestions for further work.

If it is assumed that the extrapolated curves of apparent drift velocity are valid, then the results from tubes 6 and 7 indicate that the positive ion space charges which develop as the initial avalanche crosses the gap, have the effect of retarding the growth of the avalanche. This conclusion has been obtained from a consideration of the experimental FTL curves, and of the apparent drift velocity curves, where it can be seen that high theoretical α values are present in some discharges where the apparent drift velocity is still very much smaller than the extrapolated drift velocity curve, and it is found that when the theoretical gas multiplication ($e^{\alpha d}$) in the first avalanche is increased (by changing E/p , pressure or gap distance) that the apparent drift velocity values do tend to approach (and some times even meet) the extrapolated drift velocity values.

In both tubes 6 and 7, the breakdown could sometimes have been produced by a primary avalanche, and two discharges were considered which tended to confirm this. With tube 8, however, the electron crossing time was so large, that in the time which an electron would take to cross the gap, secondary action would have been active, and α would have contributed to the current growth. Secondary

action could have been photo-electric action at the cathode (δ/α), or it could have been photo-ionization in the gas. Gas multiplications of about 10^8 have usually been quoted as being necessary for the creation of a streamer, but it has already been stated in this chapter, that exactly the same multiplication was required for breakdown to be recorded on the oscilloscope. Thus this experiment could not establish whether any streamers were created or not. The fact that secondary action was active during the time an electron takes to cross the gap, however, does imply that with the present apparatus, attempts at obtaining single avalanche breakdown (where the current growth is unaffected by any secondary effects) by increasing the gap distance will not be successful. In particular, the contribution of secondary avalanches, active as a result of the cathode photon process (δ/α) tend to complicate the discharges very considerably.

This experiment has been interesting, in that it has been shown very clearly that the development of high positive ion space charges have a very pronounced effect on the temporal growth of discharges in low pressure hydrogen at very high overvoltages. There are so many variables to be considered, however, that very little quantitative data may be obtained from a measurement of the FTL alone. In order to obtain such information concerning the actual reduction in α or drift velocity the experiment will need to be modified considerably. Perhaps a cathode made of a wire gauze would reduce the cathode photon secondary process to a negligible level. Further, using a more powerful U.V. lamp it would be interesting to determine whether it is possible to increase the initial number of electrons present at the cathode, as the pulse arrives, to a value which would affect the

FTL. Another approach which could yield very useful results would be to use a sensitive photo-cell in an attempt to follow the tip of the avalanche as it crosses the gap.

6.7 Conclusions from both low and high overvoltage experiments.

The work described in chapters 5 and 6 is quite distinct, and the nature of the breakdown processes involved in each investigation quite different. At low overvoltages, the relative importance of two possible secondary processes was determined for an E/p up to $200 \text{ V}(\text{cm}.\text{mm Hg})^{-1}$. The photon process was seen to be the predominant secondary process over the whole E/p range considered. In the high overvoltage investigation, FTL's were measured so short that the positive ion secondary process could not have been active, and sometimes not even the photon process. This latter investigation was thus concerned not so much with the secondary processes as with the primary, α , process, and the effects of the development of very high positive ion space charge fields. They were seen to retard the avalanche growth in general.

SYMBOLS

FTL	Formative time lag.
STL	Statistical time lag.
V_B	Backing voltage.
V_P	Pulse voltage.
V_S	Sparking voltage.
V_i	Ionization potential.
V_{ex}	Excitation potential.
V_m	Potential of the meta-stable state.
E_i	Ionization energy.
E_e	Energy of electron.
E	Electric field ($V.cm^{-1}$)
p	Gas pressure (mm Hg).
D	Electrode diameter (cm).
d	Gap distance (cm).
d_0	Preliminary distance electron moves.
I_0	Initial pre-breakdown current.
I_-	Electron current.
I_+	Positive ion current.
h	Plancks constant.
ν	Frequency of photon.
α	Primary ionization coefficient.
w/α	Generalized secondary ionization coefficient.
δ/α	Photon secondary coefficient.
γ	Positive ion secondary coefficient.
w_-	Electron drift velocity ($cm.sec^{-1}$).
w_+	Positive ion drift velocity ($cm.sec^{-1}$).
ϕ	Work function.
d_s	Sparking distance.

Figure Numbers

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for tubes 2 and 3.
- 30)
31) FTL curves for tube 4.
32)
- 33 ($V_D + V_P$) vs. FTL on log paper.
- 34 Proposed curves of w_+ vs. E/p .
- 35 Histograms obtained for different U.V. lamps.
- 36 FTL vs. E/p for tube 6.
- 37 Apparent drift velocity vs. E/p for tube 6.
- 38 FTL vs. E/p for tube 7.
- 39 FTL vs. E/p for tube 8.
- 40 Apparent drift velocity vs. E/p for tube 7.
- 41 Apparent drift velocity vs. E/p for tube 8.

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